Technical Paper 137

DEPARTMENT OF THE INTERIOR
FRANKLIN K. LANE, SECRETARY
BUREAU OF MINES
VAN. H. MANNING, DIRECTOR

UNIVERSITY LIBRARY
DEC 16 1916
PRINCETON, N. J

COMBUSTION IN THE FUEL BED OF HAND-FIRED FURNACES

BY

HENRY KREISINGER, F. K. OVITZ
AND
C. E. AUGUSTINE

WASHINGTON
GOVERNMENT PRINTING OFFICE
1916

The Bureau of Mines, in carrying out one of the provisions of its organic act—to disseminate information concerning investigations made—prints a limited free edition of each of its publications.

When this edition is exhausted copies may be obtained at cost price only through the Superintendent of Documents, Government Printing Office, Washington, D. C.

The Superintendent of Documents *is not an official of the Bureau of Mines.* His is an entirely separate office and he should be addressed:

SUPERINTENDENT OF DOCUMENTS,
Government Printing Office,
Washington, D. C.

The general law under which publications are distributed prohibits the giving of more than one copy of a publication to one person. The price of this publication is 15 cents.

First edition. September, 1916.

CONTENTS.

Page.
Introduction 7
Object of investigation 7
Scope of this report 7
Acknowledgment 8
Summary of results and conclusions 8
The combustion of coal 10
  Definition of combustion of coal 10
  Products of combustion of coal 10
  Where combustion in a furnace takes place 10
  Amount of air needed 11
  How air should be supplied 12
  Features in furnace design 12
    Types of commercial furnaces 13
  Reactions in fuel bed differ according to the method of feeding air and heating coal 14
Investigation of combustion in the fuel bed of a hand-fired furnace 15
  Description of apparatus 15
    Furnace 15
    Why this type of apparatus was selected 16
  Fuels used in tests 17
  Method of running tests 17
    Duration of tests 17
    Starting and closing tests 17
    Conditions during the tests 18
    Thickness of fuel bed 18
    Method of weighing fuel 18
    Measurement of air supply 18
    Measurement of temperatures 18
    Method of sampling gases 19
    Collection of tar and soot sample 20
    Position of samplers in furnace 21
    Gas samplers 21
    Gas-sample container 23
    Analysis of gas samples 23
    Determination of tar and soot 25
  Results of tests 25
  Discussion of results of tests 38
    Composition of gases in the fuel bed 38
      Effect of ash content and its distribution 45
    The three combustion processes 45
      Oxidizing zone and rate of oxidation 46
      Reducing zone and rate of reduction 46
      Distillation zone and rate of distillation 48
    Combustible leaving fuel bed in the form of soot and tar 48

Investigation of combustion in the fuel bed of a hand-fired furnace—Con.

Discussion of results of tests—Continued.

Page.
Temperature in fuel bed ... 49
Effect of rate of feeding air on the process of combustion ... 51
Rate of feeding air determines rate of combustion ... 51
For complete combustion air must be added over fuel bed ... 51
Additional air admitted through holes in fires and leaks in furnace ... 53
Admission of air through holes in fires and leaks in furnace undesirable ... 54
Relation between pressure drop through fuel bed and rate of combustion ... 55
Effect of nature of coal on pressure drop through fuel bed ... 57
Air used per pound of combustible ... 58
Effect of thickness of fuel bed on pressure drop ... 59
Fusion of ash in fuel bed ... 60
Data on combustion in fuel beds of other furnaces ... 61
Composition of gases rising from fuel bed of a hand-fired Heine boiler ... 61
Combustion process in fuel bed of a Murphy stoker ... 62
Combustion process in fuel bed of a Jones underfeed stoker ... 63
Bearing of results of tests on operation of gas producers ... 65
Explosions in boiler furnaces ... 65
Conclusion ... 67
Publications on fuel technology ... 67
Index ... 73

Original from PRINCETON UNIVERSITY

ILLUSTRATIONS.

Page.

PLATE I. Experimental furnace for studying the process of combustion in fuel bed 16
II. Coal that has been heated at 1,500° F. until volatile matter has been driven off 58
FIGURE 1. Composition of gases in the fuel bed and in the combustion space 11
2. Types of furnaces 13
3. Sections through experimental furnace 16
4. Method of measuring the thickness of fuel bed 18
5. Arrangement of apparatus for collecting samples of gases 20
6. A water-cooled gas sampler 22
7. Stand and three gas containers 24
8. Composition of gases and temperature in 6-inch fuel bed of Pittsburgh bituminous coal in a small hand-fired experimental furnace 39
9. Composition of gases and temperature in 12-inch fuel bed of Pittsburgh coal in a small hand-fired experimental furnace 40
10. Composition of gases and temperature in 6-inch fuel bed of anthracite coal in a small hand-fired experimental furnace 41
11. Composition of gases and temperature in 12-inch fuel bed of anthracite coal in a small hand-fired experimental furnace 42
12. Composition of gases and temperature in 6-inch fuel bed of coke in a small hand-fired experimental furnace 43
13. Composition of gases and temperature in 12-inch fuel bed of coke in a small hand-fired experimental furnace 44
14. Air flowing to the surface of fuel bed from top of furnace 45
15. Effect of temperature and time of contact of CO_2 with hot coke on the percentage of CO formed 47
16. Relation between the rate of combustion and pounds of air used per pound of fuel and combustible in 6-inch fuel bed 52
17. Relation between the rate of combustion and pounds of air used per pound of fuel and combustible in a 12-inch fuel bed 53
18. Relation between the pressure in the ash pit and the weight of air flowing through fuel bed 56
19. Diagram showing the relation between the apparent pressure drop and the true pressure drop through the fuel bed 60
20. Section showing zone of clinker formation in small experimental furnace 61
21. Section showing where gas samples were taken above fuel bed of Jones underfeed stoker 64

Original from PRINCETON UNIVERSITY

COMBUSTION IN THE FUEL BED OF HAND-FIRED FURNACES.

By Henry Kreisinger, F. K. Ovitz, and C. E. Augustine.

INTRODUCTION.

This report is the second of a series of publications of the Bureau of Mines on the general subject of combustion of coal in boiler furnaces and similar apparatus where coal is burned completely for the purpose of producing heat at high temperature. The first publication of this series is Technical Paper 63,[a] which treats of the combustion of gases and other combustible substances rising from the fuel bed of the side-feed type of mechanical stoker.

OBJECT OF INVESTIGATION.

The main object of the investigation described in this report was to determine the conditions governing the process of combustion in the fuel bed of a hand-fired furnace. The results of this investigation furnish data for correct design of coal-burning grates and furnaces and their efficient operation. They also cast light on the important problem of clinker trouble as related to fusibility of ash. They further indicate the possibility of a high rate of gasification of coal in gas producers, as suggested in Bulletin 7.[b]

SCOPE OF THIS REPORT.

The material presented in this paper is arranged, for convenience, in four parts, as follows: (1) General information on the combustion of coal, (2) description and results of original investigation of the process of combustion in fuel beds, (3) discussion of the results of the investigations, and (4) miscellaneous data on combustion in fuel beds.

The first part contains general information on the combustion of coal in furnaces. What combustion is and how the process of combustion takes place is explained, also how much air is needed to burn

---

[a] Clement, J. K., Frazer, J. C. W., and Augustine, C. E., Factors governing the combustion of coal in boiler furnaces: Tech. Paper 63, Bureau of Mines, 1914, 46 pp.

[b] Clement, J. K., Adams, L. H., and Haskins, C. N., Essential factors in the formation of producer gas: Bull. 7, Bureau of Mines, 1911, 58 pp.

1 pound of coal and how the air and the coal are brought together to effect combustion. The method of feeding coal and air in four types of commercial furnaces is shown and discussed.

The second part contains the description and the results of about 50 tests made in a small experimental hand-fired furnace, which was designed for an accurate study of the processes of combustion in the fuel bed. Provision was made for taking gas samples and temperature measurements at various depths in the fuel bed. Three kinds of fuels were tested in this furnace, namely, Pittsburgh coal, anthracite coal, and coke. The rate of combustion was varied from 20 to 185 pounds of fuel per square foot of grate per hour. Two thicknesses of fuel bed were used—6-inch and 12-inch. The air supplied through the grate was measured with an orifice.

The third part discusses the investigations described in the second part of the report, and includes about 40 charts that show the composition of the gases and the temperatures at different depths in the fuel bed of a hand-fired furnace, and various relations between the air supply and the rate of combustion.

Many deductions are drawn from the charts, and the significance of these deductions in the operation of industrial furnaces is shown. Many useful suggestions on the operation of such furnaces are offered.

The fourth part contains miscellaneous data on the composition of gases rising from the fuel bed of a hand-fired furnace under a steam boiler, a Murphy stoker, and a Jones underfeed stoker. It also contains a short discussion of the bearing of the results of the experiments on the operation of gas producers and explosions in boiler furnaces.

ACKNOWLEDGMENT.

Acknowledgment is made of the work of A. L. Smith, junior chemist, and E. T. Gregg, physical laboratory aid of the Bureau of Mines, in analyzing most of the gas samples and in assisting with the tests.

SUMMARY OF RESULTS AND CONCLUSIONS.

The fuel bed in most types of furnaces acts primarily as a gas producer. With a 6-inch fuel bed the oxygen in the air rising through the grate is all used up in combustion in the first 4 inches from the grate. At a distance of 4 inches from the grate the carbon dioxide content of the gases has reached or passed a maximum of 10 to 16 per cent and begins to drop. At the surface of the fuel bed the gases contain no oxygen, only 6 to 8 per cent of carbon dioxide and 20 to 32 per cent of combustible gases. The composition of the gases is practically independent of the rate of air supply. The larger the quantity of air forced through the fuel bed, the faster the fuel burns or gasifies, but the ratio between weight of air supplied and weight of fuel burned remains constant at about 7 to 1.

In general the temperature in the fuel bed is the highest 3 to 5 inches from the grate, which is also the point of maximum carbon dioxide content.

In the practical operation of boiler furnaces the significance of these results of the tests is as follows:

As most of the oxygen is consumed in the first 4 inches of the fuel bed, it is not necessary with the ordinary rates of combustion to run a fuel bed thicker than 4 to 6 inches in order to obtain a high carbon dioxide and a low oxygen content in the flue gases. The rate of combustion or gasification of coal depends on the amount of air that can be passed through the fuel bed. The thicker the fuel bed the higher is its resistance to flow of air through it and the less air can be passed through with a given chimney draft. A thick fuel bed, therefore, reduces the rate of combustion and thus reduces the capacity of the boiler.

A thick fuel bed is further undesirable because it increases the tendency of the coal to form troublesome clinker. Perhaps the only apparently defendable excuse for carrying a thick fuel bed is the fact that the chances of burning holes in the fuel bed are reduced. A skillful fireman avoids holes in the fuel bed by firing frequently and placing coal on the thin spots. A claim that fuel beds can not be kept in good condition if carried thin is a confession of neglect and lack of skill.

A fuel bed is understood to be only the layer of incandescent and freshly fired fuel and does not include the layer of dead ashes and clinker on the grate.

The ash fuses in the upper layers of the fuel bed, and as it sinks it solidifies 2 to 4 inches from the grate. In most cases the fusion occurs in a reducing or partly reducing atmosphere, consequently in studying the fusibility of ash the determinations should be made in a partly reducing atmosphere.

As at the surface of the fuel bed the gases contain 20 to 32 per cent combustible gas and practically no free oxygen, to obtain complete combustion additional air must be introduced over the fuel bed. This statement is true of all the fuels tested, including coke. As a general statement, about one-half of the 15 pounds of air used to burn 1 pound of coal in a boiler furnace is supplied through the fuel bed; the other half must be supplied over the fuel bed.

The results of the tests substantiate the statements made in the chapter on combustion of coal in Technical Paper 80.[a]

---

[a] Kreisinger, Henry, Hand-firing soft coal under power-plant boilers: Tech. Paper 80, Bureau of Mines, 1915, 83 pp.

THE COMBUSTION OF COAL.

In order to bring out more clearly that part of the problem of combustion of coal discussed in this report, the descriptions of tests and the discussions of their results are preceded by a brief discussion of the combustion of coal in general.

DEFINITION OF COMBUSTION OF COAL.

Combustion of coal is a chemical combination of the combustible ingredients of the coal with the oxygen of the air. The chief combustible ingredients of coal of economic importance are carbon and hydrogen in various combinations. Average commercial coal contains about 82 per cent of carbon and about 4 per cent of hydrogen available for combustion. Air, without which the coal could not burn, contains approximately 20 per cent of oxygen and 80 per cent of nitrogen.

PRODUCTS OF COMBUSTION OF COAL.

When carbon burns completely the product is carbon dioxide (CO_2); when it is partly burned the product is carbon monoxide (CO). If more oxygen is supplied, carbon monoxide can be burned to carbon dioxide. The hydrogen of coal burns to water vapor, which condenses to water when cooled to atmospheric temperature. The furnace gases therefore consist mainly of oxygen (O_2), nitrogen (N_2), carbon dioxide (CO_2), and carbon monoxide (CO). Besides these there may be found near the surface of fuel bed a small quantity of hydrogen (H_2), methane (CH_4), and unsaturated hydrocarbons. By analyzing the gases at successive points in a furnace the progress of combustion can be studied.

WHERE COMBUSTION IN A FURNACE TAKES PLACE.

Combustion of coal takes place partly in the fuel bed and partly in the space above the fuel bed which is commonly called the combustion space. The process of combustion in the fuel bed consists chiefly of the gasification of the fuel. The products of this gasification are mainly CO_2, CO, CH_4, and H_2. The combustible gases rising from the fuel bed are burned in the combustion space by uniting with the oxygen in the air admitted through the firing door or other openings specially provided for the purpose, and the combustion is complete if the supply of air and the size of the combustion space are sufficient. The process of combustion in a hand-fired furnace is well illustrated by figure 1, which shows the percentages of the three principal gases at various distances from the grate.

It is shown that in the fuel bed the composition of gases changes rapidly, whereas in the combustion space the change in the composition is comparatively slow and gradual. This paper is devoted to the study and discussion of the combustion processes within the fuel bed.

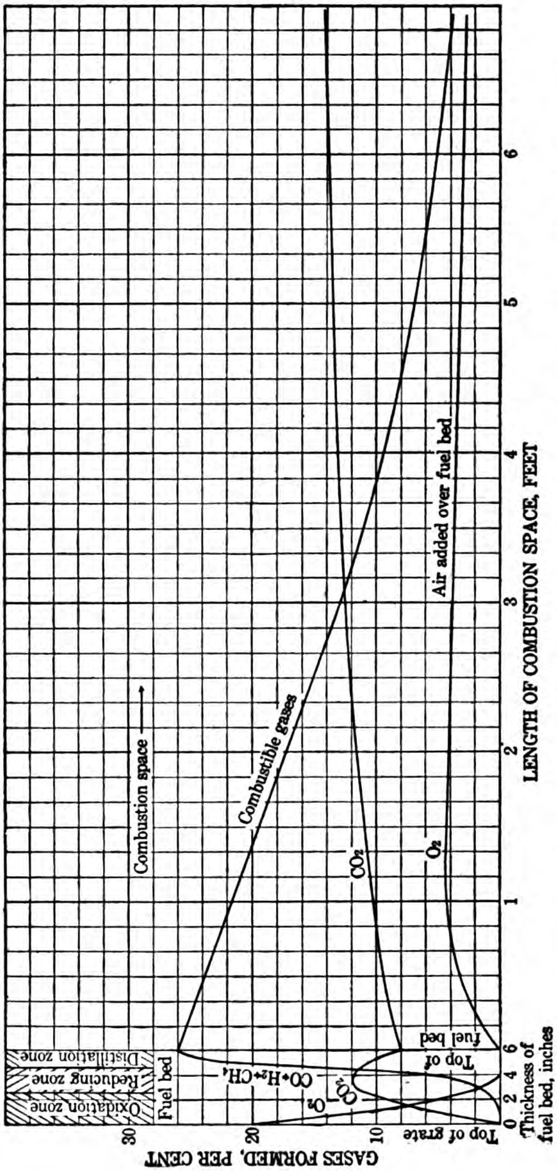


FIGURE 1.—Composition of gases in the fuel bed and in the combustion space. The gases at the top of the fuel bed contain no free oxygen and a high percentage of combustible gases, which burn in the space beyond the fuel bed after oxygen has been admitted. This diagram is a generalization of the results of many tests.

AMOUNT OF AIR NEEDED.

To burn completely 1 pound of coal in a boiler furnace requires about 3 pounds of oxygen or 15 pounds of air. One pound of coal will make a solid cube with 2¾-inch edges. Fifteen pounds of air at atmospheric pressure and temperature occupies a volume of about

200 cubic feet, which is approximately the volume of a 6-foot cube. The volumes of these two cubes show the relative volumes of coal and air that must be fed into the furnace to obtain complete combustion.

HOW AIR SHOULD BE SUPPLIED.

In the combustion of coal both the amount of air and the way in which the air is supplied are important. The air may be introduced to the coal at an average distance of several feet or of a small fraction of an inch, the time required for combustion in either case depending on this average distance through which the oxygen has to pass in order to come in contact with the surfaces of the coal.

Thus, for example, if a 2¾-inch cube of coal were placed in the center of a 6-foot cubic container filled with air and kept hot, it would burn completely. However, combustion would be slow and might require several hours, although there would be enough air in the container to burn all the coal. The combustion would be slow because the oxygen is supplied at an average distance of more than 2 feet from the surfaces of the small cube of coal, so that most of the oxygen would have to pass this average distance of 2 feet by the slow process of diffusion, and the products of combustion, chiefly CO_2, would have to be moved away a like average distance by the same slow process.

If, however, the 200 cubic feet of air required to burn the cube of coal were passed at high velocity in thin streams one-sixteenth inch thick over the surfaces of the cube of burning coal, combustion would be rapid, because the oxygen in these streams of air would have to move an average distance of only one thirty-second of an inch to get in contact with the coal. Furthermore, the oxygen would be greatly aided in passing through this average distance of one thirty-second inch by the eddy currents formed by the high velocity of the stream of air, and would not depend on the slow process of natural diffusion.

Therefore, for rapid combustion, the air must be supplied in thin streams of high velocity over the surfaces of the coal. In general it may be stated that the rate of burning depends entirely on the rate at which oxygen is brought into contact with the coal.

FEATURES IN FURNACE DESIGN.

The devising of the best method of bringing the oxygen and the coal together, or, in other words, the feeding of coal and air into the furnace, is the dominant feature in the problem of furnace design. As coal must be heated to its ignition temperature before it can be made to burn, another important feature is the method and the rate of heating the coal. There are other important features in furnace design, but the two mentioned are the most important.

TYPES OF COMMERCIAL FURNACES.

There are several more or less satisfactory methods of feeding coal and air and of heating the coal in ordinary boiler furnaces. The principal types of furnace feeds are shown in figure 2, in which the direction of feeding the coal and the air into the furnace and the direction in which heat is imparted to the coal are shown by arrows.

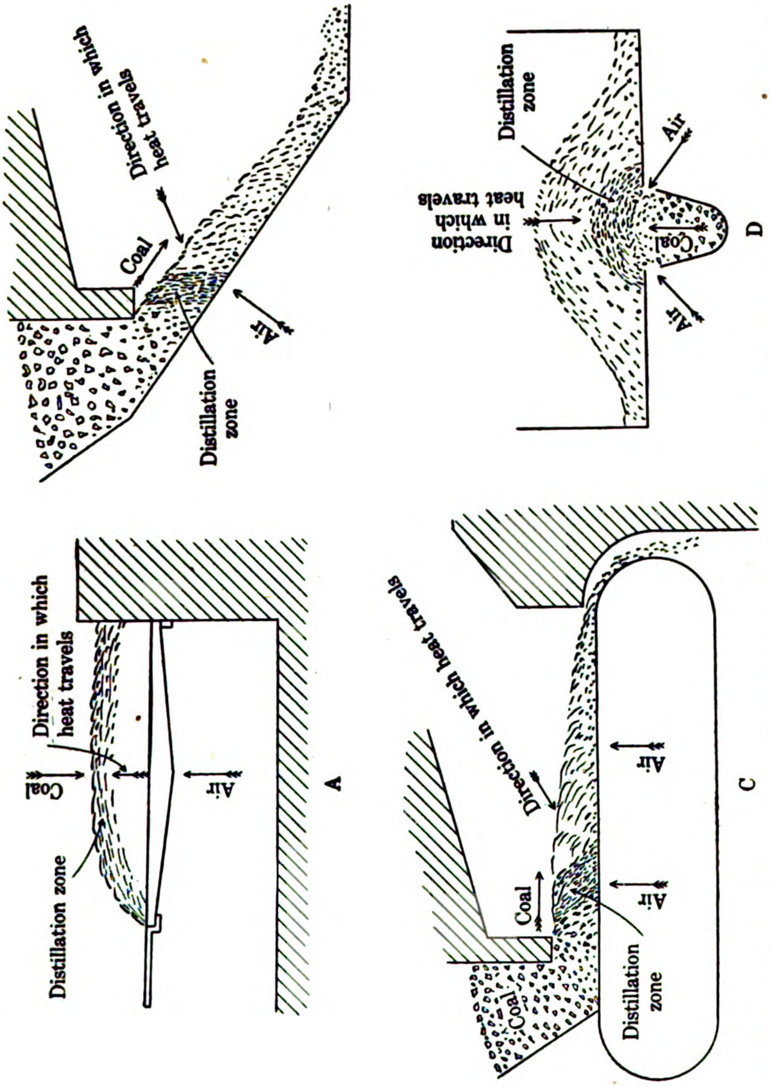

Direction in which heat travels
Coal
Air
Distillation zone
Direction in which heat travels
Distillation zone
Air
Coal
Air
D
Direction in which heat travels
Coal
Air
Distillation zone
A
Direction in which heat travels
Coal
Coal
Air
Air
Distillation zone
C

FIGURE 2.—Types of furnaces. A, Hand-fired; B, side feed by gravity and agitation of grate bars; C, side feed with chain grates; D, underfeed. The arrows indicate the direction of feeding coal and air, and also the direction in which the heat travels. The distillation zone is indicated by dark shading.

Diagram A shows the method of feeding coal and air to hand-fired furnaces. The coal is fed intermittently from above and the air is supplied in the opposite direction and at approximately uniform rate from beneath the grate. The coal is heated from below by contact with the hot fuel bed and the hot products of combustion that rise from it. The rate of heating is high, the coal being heated to the furnace temperature within one or two minutes after firing. The volatile matter is distilled in the thin zone of the freshly fired coal at the top of the fuel bed. As will be shown later, there is no free oxygen in this zone and distillation takes place in a reducing atmosphere.

Although the hand-fired furnace is fairly satisfactory for a coal low in volatile matter, intermittent feeding and rapid heating are very objectionable for a coal high in volatile matter because they tend to produce smoke.

Diagram B shows a type of side feed in which the coal is moved down by gravity and the shaking of the grate. The Roney and the Murphy stokers represent this type. Air is fed from below at right angles to the direction of the coal feed. The heating of the coal, which is mostly by conduction through the fuel and by radiation from the arch, proceeds nearly in the opposite direction to that of the feed of coal and at right angles to the feed of air. It is gradual and extends over several minutes. The hot products of combustion do not come in contact with the fresh coal. The volatile matter is distilled in a wide zone extending vertically the full thickness of the fuel bed near the place where the coal enters the furnace and where the atmosphere contains a large percentage of oxygen. Because the coal is fed uniformly and heated slowly, and because the distillation of volatile matter takes place largely in an oxidizing atmosphere, this type of furnace is well adapted to high-volatile coals.

The chain grate shown in diagram C is another side-feed stoker that is in extensive use. With a chain grate the feeding of coal is more positive, because the entire grate moves in the direction of the feed.

Diagram D shows the underfeed type of stoker, in which both the coal and the air are fed from below in approximately the same direction, and the heating of the coal proceeds from above in the opposite direction. The coal is heated mostly by conduction through the fuel against the stream of air, and distillation of volatile matter takes place in an oxidizing atmosphere. This type of stoker is well adapted to burning high-volatile coals.

In all these devices the air is passed rapidly in fine streams through the fuel bed, the velocity ranging from 15 to 75 feet per second.

REACTIONS IN FUEL BED DIFFER ACCORDING TO THE METHOD OF FEEDING AIR AND HEATING COAL.

In the devices just described the reaction between the oxygen and the combustible part of coal probably follows different courses, according to the method of feeding coal and air, according to the rate of

Original from PRINCETON UNIVERSITY

heating the coal, and according to the kind of atmosphere, whether oxidizing or reducing, in which the volatile matter is distilled. This report treats mainly of the reactions in the fuel bed of the hand-fired furnace shown in diagram A, figure 2.

INVESTIGATION OF COMBUSTION IN THE FUEL BED OF A HAND-FIRED FURNACE.

In order to obtain data for studying the process of combustion in the fuel bed of such a furnace 50 tests were made with a small hand-fired furnace at the experiment station of the Bureau of Mines in Pittsburgh, Pa. In these tests samples of gases were taken from the fuel bed at intervals of 1½ inches from the grate, and temperatures were measured at the points where the samples were taken. The air supplied through the grate was measured with an orifice box. Two thicknesses of fuel bed were used, 6-inch and 12-inch, and three kinds of fuel were tested, Pittsburgh coal, anthracite coal, and coke. The rates of combustion varied from 20 to 185 pounds per square foot of grate per hour.

DESCRIPTION OF APPARATUS.

Plate I shows the general arrangement of the apparatus, which consisted chiefly of a cylindrical furnace placed on an air-tight rectangular ash box that had an orifice box attached on one side. The air was supplied under pressure through the orifice box into the ash box and up through the grate to the fuel bed. Several gas samplers were inserted radially into the furnace, as shown in Plate I. These samplers were water-cooled and were connected with rubber hose to a water supply and drain pipe, the latter serving also as a support for the stack. To the right is shown a table on which are gas-collecting devices.

FURNACE.

Figure 3 shows two sections through the apparatus. The furnace was a steel cylinder 22½ inches in diameter and 30 inches high, lined with a 4½-inch layer of fire brick. The space inside the lining was 13½ inches in diameter, giving approximately 1 square foot of grate area. In the wall of the furnace were several ⅝-inch holes for the insertion of gas samplers. The holes were in planes spaced 1½ inches apart in the vertical direction and distributed radially around the furnace, as shown in figure 3.

The grate was in two sections, each of which could be shaken independently of the other. The air spaces were about one-half inch wide and constituted approximately 60 per cent of the total grate area. The ash box had a tight-fitting door for the removal of ashes.

The fuel was charged through the opening at the top of the furnace. The air was supplied to the orifice box under a pressure of 8 to 20 inches of water by a cupola blower which was belted to an electric motor. The flow of air through the orifice was controlled with a gate placed in the duct between the fan and the orifice box.

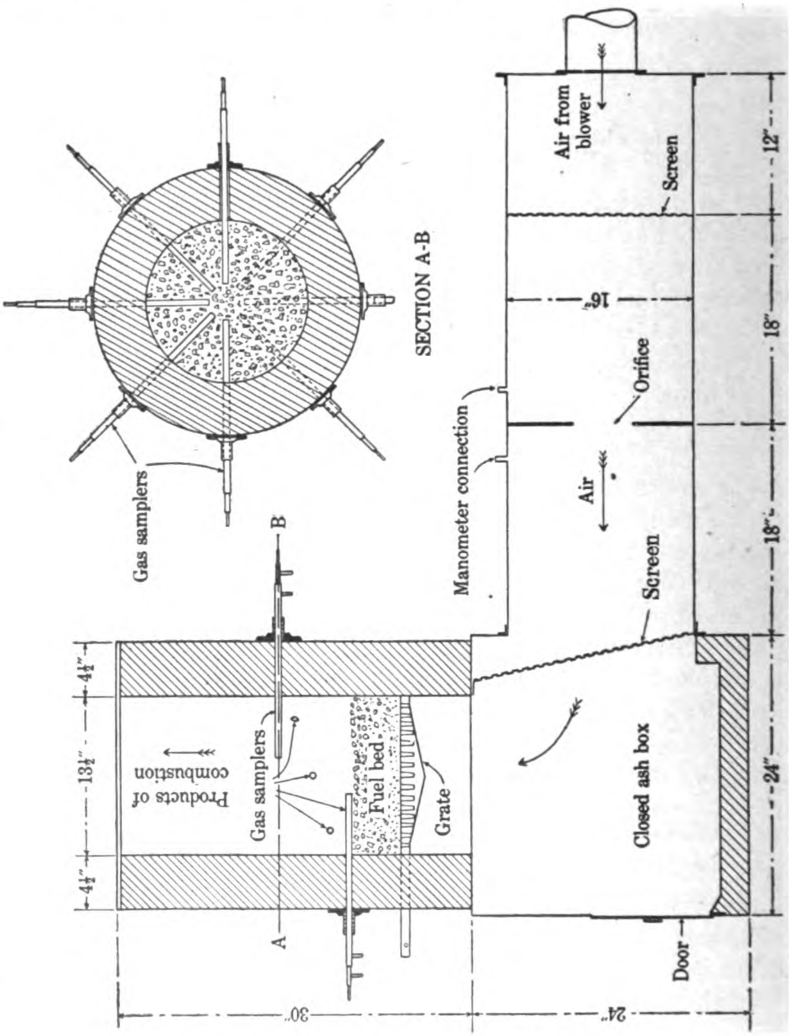
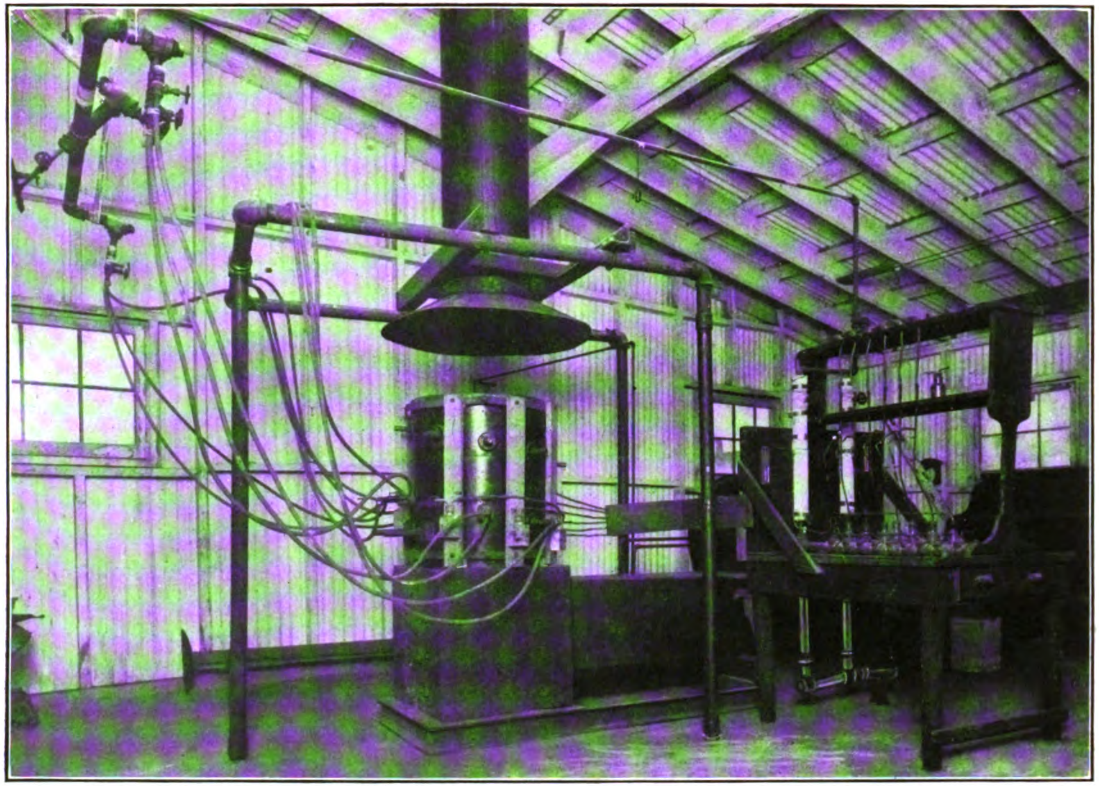


FIGURE 3.—Sections through experimental furnace.

WHY THIS TYPE OF APPARATUS WAS SELECTED.

This type of apparatus was selected because with it all factors could be easily controlled. The grate area was small, so that the fuel bed could be kept in uniform condition over the entire grate, and yet was large enough so that there need be no hesitation about applying the results to large hand-fired furnaces. In fact, the grate

Original from PRINCETON UNIVERSITY



EXPERIMENTAL FURNACE FOR STUDYING THE PROCESS OF COMBUSTION IN FUEL BED. ON THE RIGHT IS SHOWN A TABLE AND EQUIPMENT FOR COLLECTING GASES.

was nearly as large as in many house-heating furnaces and boilers. The furnace was easily accessible from all directions, an important feature in sampling gases and measuring temperatures. A further advantage was that the tests could be started in a short time and needed to be only 1 to 3 hours long to give sufficient accuracy.

FUELS USED IN TESTS.

Three kinds of fuel were used in the tests—Pittsburgh coal, anthracite, and metallurgical coke. All three fuels were sized by passing them over 1-inch square-mesh screen and through 1½-inch screen of the same type.

The results of analyses of the three fuels are as follows:

Results of analyses of three fuels used in tests.

PROXIMATE ANALYSIS OF FUEL AS FIRED.

Constituent.	Pittsburgh coal.	Anthracite.	Coke.
	Per cent.	*Per cent.*	*Per cent.*
Moisture	2.28	2.76	0.71
Volatile matter	34.27	5.28	1.42
Fixed carbon	52.63	81.62	81.26
Ash	10.82	10.34	16.61

ULTIMATE ANALYSIS OF DRY FUEL.

Hydrogen	4.99	2.42	0.27
Carbon	74.98	83.07	80.23
Nitrogen	1.38	.93	.72
Oxygen	5.77	2.10	.14
Sulphur	1.81	.85	1.91
Ash	11.07	10.63	16.73
B. t. u.	13,559	13,392	11,635

METHOD OF RUNNING TESTS.

DURATION OF TESTS.

The duration of tests varied from 1 to 3 hours, depending on the rate of combustion. With low rates the test was longer and with high rates it was shorter.

STARTING AND CLOSING TESTS.

Before starting the test, the fuel bed was built to the desired thickness and the furnace was heated. This preparation usually took 20 to 30 minutes. The grate was then shaken, all the ash removed from the ash box, and the test was started.

The test closed with the fuel bed of the same thickness as it was at the start. The ash was taken out of the ash box and weighed. The fuel on the grate was allowed to burn out and the clinkers that were left were taken out, weighed, and charged to the test.

Original from PRINCETON UNIVERSITY

CONDITIONS DURING THE TESTS.

During the test the thickness of the fuel bed, the rate of charging the fuel, and the rate of supplying air were kept uniform. Fuel was charged in equal quantities at intervals of 1 to 5 minutes. The intervals were long with low rates of combustion and short with high rates.

THICKNESS OF FUEL BED.

The thickness of fuel bed was determined by measuring with a special hook the distance of the surface of the fuel bed below the top of the furnace. The method is illustrated in figure 4. The determination was reliable to within one-half inch.

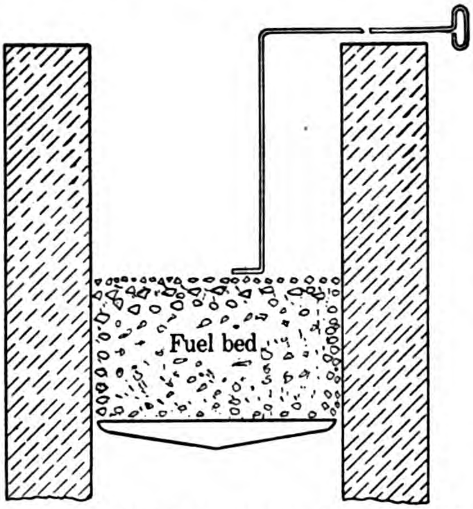


FIGURE 4.—Method of measuring the thickness of fuel bed.

METHOD OF WEIGHING FUEL.

The fuel was placed in a steel box on a platform scale and each charge was weighed and recorded separately. The time of each firing was also recorded.

MEASUREMENT OF AIR SUPPLY.

The air supplied through the grate was measured with an orifice having an edge one-sixteenth inch thick. The pressure drop through the orifice was obtained with a recording differential hydro gage. The gage magnified the pressure drop five times and recorded it on a rectangular chart. The weight of air was computed from experimental values determined by Durley.[a]

MEASUREMENT OF TEMPERATURES.

Usually four sets of temperature measurements were taken on each test, one being taken immediately before each of the three sets of gas samples and one after the third set of samples. The temperatures were measured with a Wanner optical pyrometer through the same openings that the gas samples were taken. Before the measurements were made the grate was shaken to remove excess ash from the fuel

---

[a] Durley, R. J., On the measurement of air flowing into the atmosphere through circular orifices in thin plates and under small differences of pressure: Trans. Am. Soc. Mech. Eng., vol. 27, 1906, p. 193.

Digitized by Google Original from PRINCETON UNIVERSITY

bed; the gas samplers were then pulled out one by one and the temperature was measured by sighting the pyrometer into the small tunnels left by the samplers in the fuel bed. In case the small tunnel caved in after the sampler was pulled out, the sampler was pushed back into the fuel bed and a new tunnel was made. To prevent the gases from flowing out of the furnace during the temperature measurement the opening was closed on the outside with a thin, clear glass plate and the temperature was read through the plate. The presence of the glass did not affect the temperature readings appreciably. The temperatures were not taken simultaneously at all points, but in rapid succession, starting with the hole nearest to the grate. On the average the readings at the different holes were taken about 30 seconds apart.

METHOD OF SAMPLING GASES.

All gas samples in each set were collected simultaneously with water-cooled samplers inserted into the fuel bed at various heights from the grate. The gas was collected in glass receptacles over mercury. Usually three sets of samples were collected during each test in order to eliminate the effect of any irregularities in the fuel bed on the composition of the gas sample. The duration of collecting the samples was three to five minutes. The grate was shaken and the temperature in the fuel bed was measured two to five minutes before each set of samples was collected.

The general scheme of collecting a sample of gas is shown diagrammatically in figure 5. The apparatus consisted essentially of a water-cooled sampler, two wash bottles partly filled with water, a gas container, and a suction pipe. These parts were connected together with ¼-inch lead and copper tubing. A steam ejector kept the pressure in the suction pipe reduced and caused a continuous current of gas to flow from the furnace through the system. A tube leading to the wash bottle extended below the level of the water in the bottle so that the flow of gas made itself visible by bubbling through the water. If for any reason the flow of gas stopped, the operator could notice it immediately by watching the wash bottle. A part of this current of gas, deflected at *C*, was made to flow into the gas container by allowing the mercury to run out of it. The gas collected in the container constituted the sample that was analyzed. Before starting to collect the gas the air in the tube leading to the container was exhausted by opening the pinchcock *A* and closing the pinchcock *B*.

A U-tube monometer was connected to the suction pipe to indicate the reduction in pressure, thereby facilitating the control of the gas-collecting apparatus.

COLLECTION OF TAR AND SOOT SAMPLE.

A filter placed between the water-cooled sampler and the lead-pipe connection caught the tar and solid particles carried in the gas, preventing them from clogging the connection.

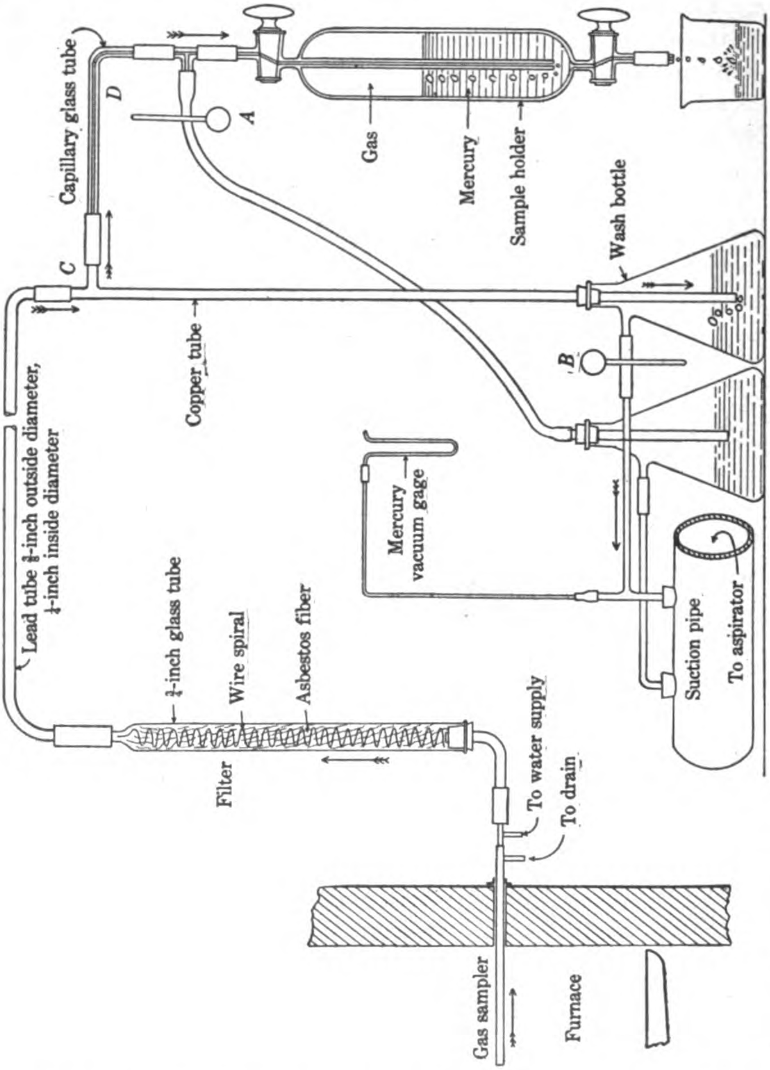


FIGURE 5.—Arrangement of apparatus for collecting samples of gases. Not drawn to scale, important details are enlarged.

Similar filters were used to determine the amount of soot and tar in the gases in and above the distillation zone of the fuel bed. The filters were filled with asbestos fiber which had been previously burned to remove all combustible material. The fiber was packed around a brass-wire spring, shown in figure 5, which prevented the fiber from being drawn by the moving gases to one end of the filter tube and clogging it. When the determination of soot and tar was desired, a clean sampler was inserted into the furnace and the volume of gas drawn through the sampler and filter was measured by a gas meter placed between the wash bottle and the suction pipe. After a sample had been collected, the soot and tar deposited in the sampler were cleaned out, and together with the soot and tar trapped in the filter were considered a part of the composite sample of soot, tar, and gases.

Three of such soot and tar samples were collected with the first two sets of gas samples on several of the tests made with Pittsburgh coal. One of the samples was collected 1½ inches below the surface, one at the surface, and one 1½ inches above the surface of the fuel bed.

POSITION OF SAMPLERS IN FURNACE.

The samplers were inserted into the furnace through ⅝-inch holes in the furnace wall provided for the purpose. They were distributed radially around the wall of the furnace at vertical intervals of 1½ inches from the grate, as shown in figure 3; that is, the first sampler was 1½ inches, the second 3 inches, and the third 4½ inches from the grate, and so on. The inlets of the samplers were placed 1½ inches from the center of the furnace. The object in distributing the samplers radially was to avoid the localization of the disturbance of the fuel bed by the samplers, and to obtain more space on the outside of the furnace for their manipulation. With this arrangement the tendency for channels to form in the fuel bed was much less than if all the samplers had been in one vertical plane.

GAS SAMPLERS.

The construction of one of the gas samplers is shown in figure 6. The sampler, which was water-cooled in order to prevent its destruction by heat, was made of three thin-wall copper tubes placed within one another. The joint inserted into the fuel bed was brazed, all other joints were soldered. The water entered through the middle tube which surrounded the smallest one used for drawing the gas sample, and left through the outer tube. The entering cold water cooled the gases rapidly as soon as they entered the gas tube, preventing any reactions among the gases or between the gases and the metal of the sampler, so that the gases were of the same composition when collected as they were when in the fuel bed. The gas tube was of comparatively large diameter to prevent stoppage by condensed tar and soot, a difficulty which was particularly liable to occur in the samplers near the surface of the fuel bed. Condensed water vapor was carried with the current of the gases into the filter attached to the outside end of the sampler.

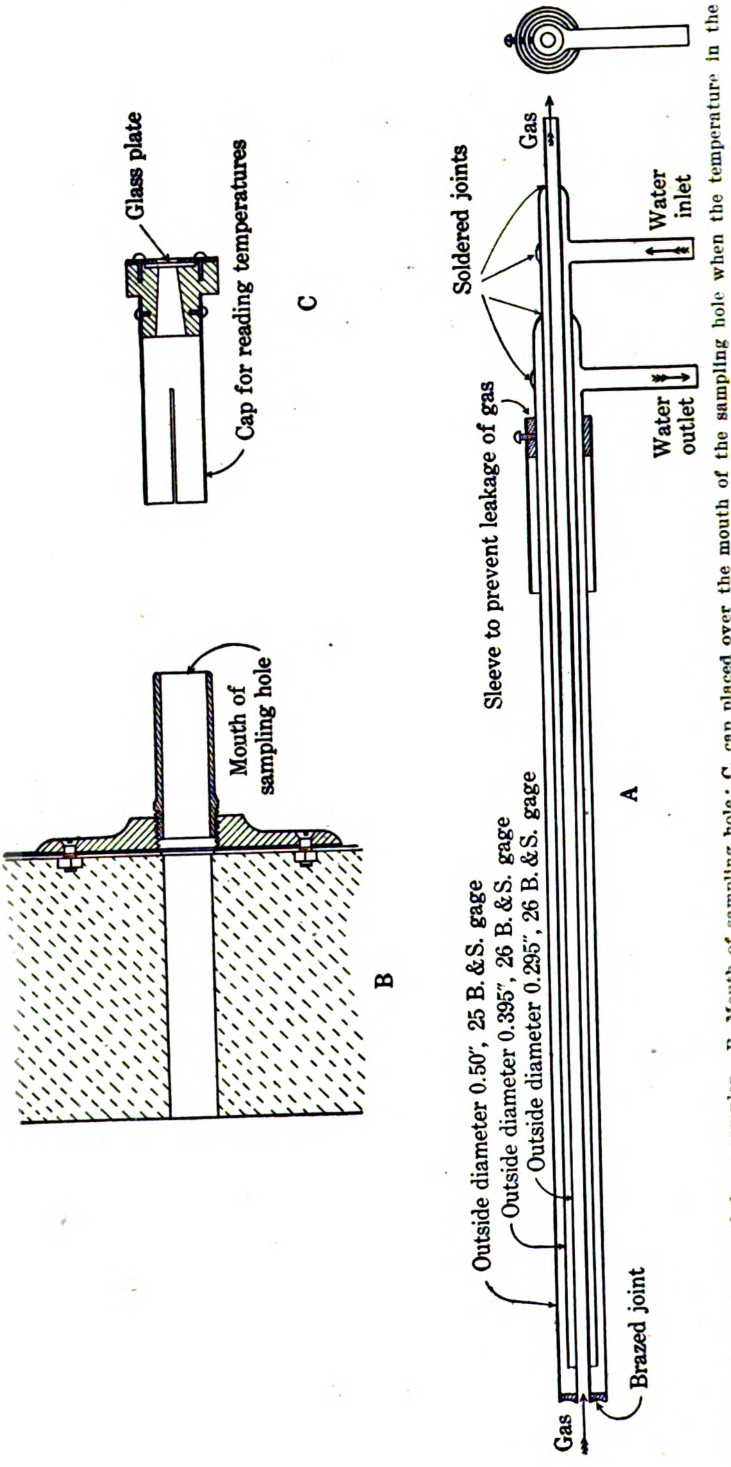

Glass plate
Cap for reading temperatures
C
Mouth of sampling hole
B
Soldered joints
Gas
Water inlet
Water outlet
Sleeve to prevent leakage of gas
Outside diameter 0.50", 25 B. & S. gage
Outside diameter 0.395", 26 B. & S. gage
Outside diameter 0.295", 26 B. & S. gage
A
Brazed joint
Gas

FIGURE 6.—A water-cooled gas sampler. B, Mouth of sampling hole; C, cap placed over the mouth of the sampling hole when the temperature in the fuel bed was read.

The sampler was provided with a sleeve which fitted tightly over the mouth of the sampling hole in the furnace wall and prevented leakage of gases from the furnace. When the sampler was pulled out of the furnace, in order to take a temperature reading, a cap fitted with a glass plate was slipped over the projecting mouth of the sampling hole. This cap, shown in figure 6, prevented leakage of gas while the temperature reading was being taken.

GAS-SAMPLE CONTAINER.

The gas-sample container served both as part of the sampling device and as a holder for the gas after collection. Figure 5 shows a container in upright position. It was a glass vessel of about 150 c. c. capacity, so constructed that the mercury flowed out under a constant head. Inasmuch as the composition of the gas at any point was constantly changing, it was necessary to collect an equal volume of gas over equal periods of time to obtain an average sample at the point of collection. As long as the surface of the mercury was above the gas inlet an equal volume of mercury would flow out during each equal interval of time and be replaced by the same volume of gas.

The period of sampling could be regulated by controlling the flow of mercury from the container. A small-bore capillary tube or a glass tube drawn out to a small tip and attached to the outlet of the container was a satisfactory means of control. By this method a representative sample over a period of 5 to 45 minutes could be collected in a 150 c. c. container.

The vessel also served as a safe and convenient holder for storing the sample. The mercury formed a seal between the gas and stopcocks as long as its level did not fall below the opening of the inner tube or gas inlet. The seal prevented leakage through the stopcocks. All danger of leakage into the container was eliminated by placing the sample under slight pressure by forcing in some mercury through the gas inlet tube. In this manner a sample could be stored safely.

For convenience and safety in handling the glass vessels they were mounted on portable wooden stands, three containers on each stand. Figure 7 illustrates the stand and method of mounting.

ANALYSIS OF GAS SAMPLES.

The samples of gas were analyzed for CO_2, O_2, CO, H_2, CH_4, and unsaturated hydrocarbons. On tests with coke and anthracite coal no unsaturated hydrocarbons were found, and this determination was omitted in the later tests with these fuels.

The analyses were made with a modified Hempel apparatus, the gas being analyzed over mercury. The measuring burette was water

Digitized by Google Original from PRINCETON UNIVERSITY

jacketed and provided with a Pettersson pressure and temperature compensating tube. Determinations of H_2 and CH_4 were made by the slow-combustion method with a heated platinum coil.

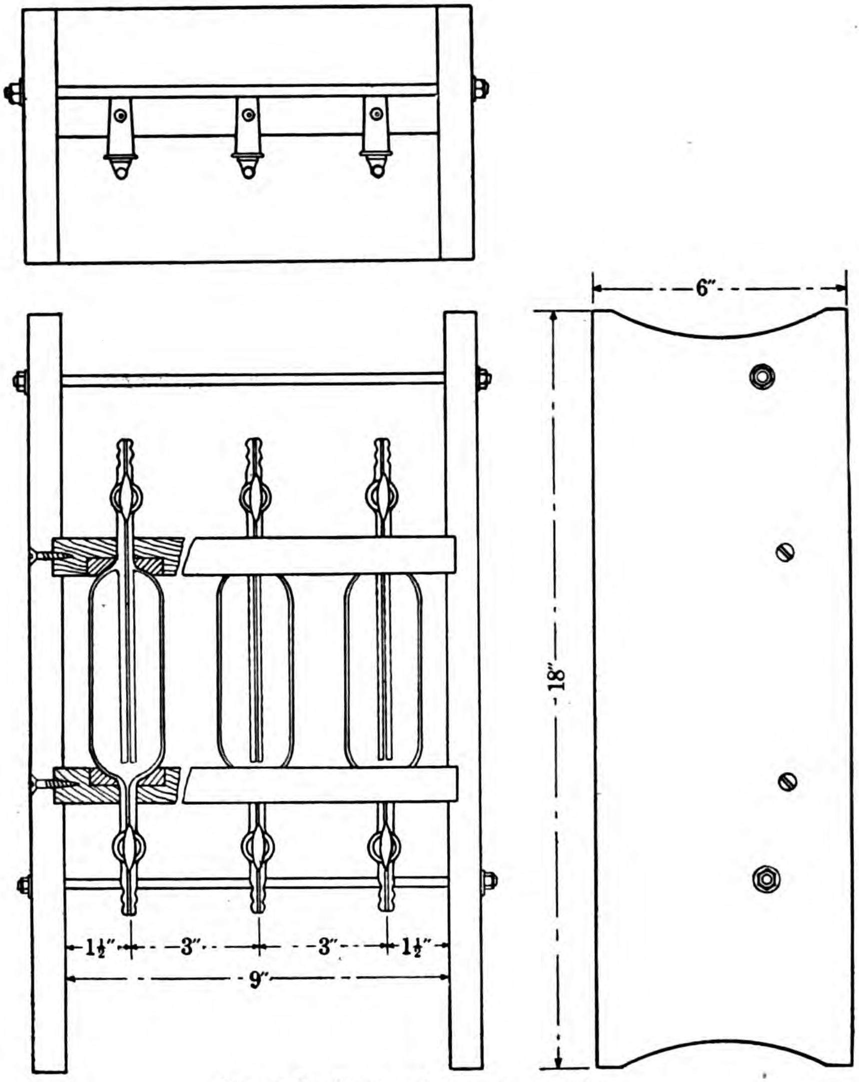


FIGURE 7.—Stand and three gas containers.

The determination of CO_2, O_2, unsaturated hydrocarbons, and small quantities of CO is within +0.1 or −0.1 per cent of the volume of the sample. With large amounts of CO, requiring more than one pipette for absorption, and with CH_4 and H_2, the error may at times reach +0.2 or −0.2 per cent.

DETERMINATION OF TAR AND SOOT.

The tar was separated from the soot by extraction with hot benzol in Soxhlet extraction apparatus. The soluble part was considered tar and the insoluble combustible part soot. The results are not strictly accurate, as benzol combines to some extent with the tar, forming insoluble compounds, thereby yielding low results for tar and high results for soot.[a] However, the error from this source is not over 5 per cent of the tar.

The tar and soot deposited in the sampler and filter were removed by cleaning thoroughly with asbestos fiber and benzol. The asbestos fiber from the filter and that used in cleaning, which contained all the tar and soot, were placed in an alundum thimble and extracted on a sand bath until the benzol was colorless. The tar, contained in the extraction flask, was freed from benzol by passing dry air at room temperature through the flask until the loss was less than 1 milligram on successive weighings one-half hour apart. The difference in weight between the flask and tar and the clean, dry flask is the weight of tar. While the tar was being freed from benzol some of the light oils contained in it were carried away with the benzol and lost, but the error from this source is not greater than 2 per cent.

After extraction, the alundum thimble containing the soot mixed with asbestos fiber was dried to constant weight at 105° to 110° C., and the soot burned off in a muffle furnace at red heat. The loss in weight due to burning is the amount of soot.

RESULTS OF TESTS.

The results of the tests made on the small furnace are given in a convenient form in Table 1. The tests are arranged in three groups, first, according to the kind of fuel, and second, according to the thickness of fuel bed. A full explanation of each item of the table is given in the following paragraphs:

Column 1 gives the serial number of each test. Some of the early tests were not reliable in all items, and therefore the results of these tests are not presented in the table.

Column 2 gives the average thickness of fuel bed during the test.

Column 3 gives the percentage of combustible in the fuel as fired. In this report the word " combustible " means moisture-free and ash-free coal.

Column 4 gives the duration of test in minutes. This duration includes only the test proper and does not include the time taken in preparing the fuel bed for the test.

---

[a] Weiss, J. M., Free carbon, its nature and determination in tar products: Jour. Ind. Eng. Chem., vol. 6, 1914, p. 279.

Original from PRINCETON UNIVERSITY

Column 5 gives the average pressure of air in the ash pit in inches of water.

Column 6 gives the weight in pounds of fuel fired per hour.

Column 7 gives the weight in pounds of combustible burned per hour. The values given in the table are obtained by multiplying the value in column 6 by the value in column 3 and subtracting from the product the combustible in refuse fallen into ash pit.

Column 8 gives the weight of air forced through the fuel bed per hour as measured with the orifice.

Column 9 gives the weight of air forced through the fuel bed per pound of fuel fired. The values are obtained by dividing the values in column 8 by those in column 6.

Column 10 gives the weight of air forced through the fuel bed per pound of combustible burned. The values in this column are obtained by dividing the values in column 8 by those in column 7.

Column 11 gives the location where the samples of gas were taken. The figures are the vertical distance, in inches, of the place sampled from the grate.

Columns 12 to 19 give the average composition of gases in the fuel bed. Each composition given in the table is the average analysis of three different samples.

Column 20 gives the weight of tar in grams per cubic foot of gas. The weight given in the table is the average of two samples collected at different periods of the test.

Column 21 gives the weight of soot in grams per cubic foot of gas. The weight given in the table is the average of two samples collected at different periods of the test.

Column 22 gives the temperatures in the fuel bed at the distances from the grate given in column 11. The temperatures given in the table are the averages of four readings taken at different times.

Column 23 gives the weight of air per pound of combustible computed from the gas analysis at the point given by column 11. The weight was computed from the following formula:

$$W=3.03C\frac{N_2}{CO_2+CO+CH_4+n(C_nH_{2n})}$$

In the formula C is the percentage of carbon in the combustible, and N_2, CO_2, CO, CH_4, and C_nH_{2n} are the percentages of these constituents in the gases.

TABLE 1.—*Results of tests with small experimental furnace*

PITTSBURGH BITUMINOUS COAL.

Test No.	Thickness of fuel bed.	Combustible in fuel as fired.	Duration of test.	Pressure in ash pit, inches of water.	Fuel fired per hour.	Combustible burned per hour.	Air forced through fuel bed per hour.	Weight of air per pound of fuel fired, measured with orifice.	Weight of air per pound of combustible, measured with orifice.	Distance of sample from grate.	Average volume composition of gases in fuel bed.								Weight of tar per cubic foot of gas.	Weight of soot per cubic foot of gas.	Temperature in fuel bed.	Weight of air per pound of combustible, computed from gas analysis.
											Carbon dioxide (CO$_2$).	Unsaturated hydrocarbons.	Oxygen (O$_2$).	Carbon monoxide (CO).	Methane (CH$_4$).	Hydrogen (H$_2$).	Nitrogen (N$_2$).	Total gaseous combustible.				
1	2	3	4	5	6	7	8*	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	In.	*P. ct.*	*Min.*		*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*In.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*Grams.*	*Grams.*	*°F.*	*Lbs.*
46	6	87.14	67	0.1	20.5	16.9	132	6.5	7.8	1.5	16.4	0.0	1.3	5.2	0.0	0.2	76.9	5.4	......	......	2,453	......
										3.0	13.3	.0	.1	12.1	.0	.4	74.1	12.5	......	......	2,329	......
										4.5	9.8	.1	.1	17.7	.1	1.2	71.0	19.1	......	......	1,989	6.6
										6.0	6.7	.4	.2	20.5	2.0	6.9	63.3	29.8	......	......	1,969	5.5
										7.5	8.0	.5	1.6	16.2	1.5	5.2	67.0	23.4	......	......	1,927	......
52	6	87.91	290	.1	22.3	17.8	127	5.7	7.1	1.5	15.9	.0	3.7	1.5	.0	.4	78.5	1.9	......	......	2,383	......
										3.0	13.2	.0	.0	12.5	.2	1.0	73.1	13.7	......	......	2,356	......
										4.5	10.6	.3	.3	15.1	.9	4.3	68.5	20.6	0.549	0.227	2,165	6.5
										6.0	9.1	1.8	.2	13.7	3.7	9.3	62.2	28.5	.528	.482	2,199	5.3
										7.5	9.4	1.0	.5	12.8	2.9	9.4	64.0	26.1	.200	.450	2,271	......
27	6	86.90	60	.05	23.0	17.7	129	5.6	7.3	1.5	15.1	.0	3.2	3.8	.1	.1	77.7	4.0	......	......	2,187	......
										3.0	14.5	.1	.2	9.3	.3	.7	74.9	10.4	......	......	1,974	......
										4.5	11.1	1.3	.4	12.3	1.3	3.4	70.2	18.3	......	......	1,879	6.6
										6.0	11.4	1.0	.5	10.2	1.8	5.1	70.0	18.1	......	......	2,016	7.0
										7.5	11.9	.6	1.4	8.1	1.3	3.5	73.2	13.5	......	......	2,093	......
28	6	86.90	76	.08	30.0	22.8	190	6.3	8.3	1.5	15.8	.0	1.7	4.9	.1	.4	77.1	5.4	......	......	2,349	......
										3.0	13.5	.0	.3	10.7	.4	.6	74.5	11.7	......	......	2,208	......
										4.5	8.6	.8	1.0	15.0	2.3	8.4	63.9	26.5	......	......	2,187	5.9
										6.0	9.1	1.1	1.0	14.6	3.5	7.3	63.4	26.5	......	......	2,151	5.5
										7.5	9.5	1.7	.6	14.2	1.7	5.7	66.6	23.3	......	......	2,197	......

TABLE 1.—*Results of tests with small experimental furnace.*

PITTSBURGH BITUMINOUS COAL—Continued.

Test No.	Thickness of fuel bed.	Combustible in fuel as fired.	Duration of test.	Pressure in ash pit, inches of water.	Fuel fired per hour.	Combustible burned per hour.	Air forced through fuel bed per hour.	Weight of air per pound of fuel fired, measured with orifice.	Weight of air per pound of combustible, measured with orifice.	Distance of sample from grate.	Average volume composition of gases in fuel bed.								Weight of tar per cubic foot of gas.	Weight of soot per cubic foot of gas.	Temperature in fuel bed.	Weight of air per pound of combustible, computed from gas analysis.
											Carbon dioxide (CO_2).	Unsaturated hydro-carbons.	Oxygen (O_2).	Carbon monoxide (CO).	Methane (CH_4).	Hydrogen (H_2).	Nitrogen (N_2).	Total gaseous combustible.				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	In.	*P. ct.*	*Min.*		*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*In.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*Grams.*	*Grams.*	*°F.*	*Lbs.*
53	6	87.91	201	0.23	47.5	38.8	280	6.0	7.2	1.5	8.9	0.0	11.4	0.7	0.0	0.2	078.8	0.9	......	......	2,575	21.0
										3.0	11.4	.0	7.2	3.4	.0	.3	77.7	3.7	......	......	2,606	13.4
										4.5	15.2	.2	.4	8.3	.1	.5	75.3	9.1	0.006	0.048	2,615	8.0
										6.0	10.5	.1	.8	14.5	.8	3.9	69.4	19.3	.241	.369	2,584	6.8
										7.5	8.9	.8	.2	16.0	2.0	8.4	63.7	27.2	.335	.892	2,608	5.7
54	6	87.91	157	.41	63.4	52.2	403	6.3	7.7	1.5	9.3	.0	10.9	.7	.0	.1	79.0	.8	......	......	2,698	......
										3.0	15.0	.0	1.3	7.1	.1	.3	76.2	7.5	......	......	2,592	......
										4.5	11.1	.4	1.9	12.3	.1	.4	73.8	13.2	.008	.036	2,628	7.8
										6.0	12.1	.3	1.4	10.5	.7	2.4	72.6	13.9	.107	.215	2,647	7.8
										7.5	11.7	.7	.0	10.3	1.4	6.9	69.0	19.3	.211	.669	2,581	......
39	6	87.14	44	.36	79.0	63.0	485	6.1	7.9	1.5	12.3	.0	7.6	.8	.0	.2	79.1	1.0	......	......	2,602	......
										3.0	11.0	.0	1.5	13.3	.2	.3	73.7	13.8	......	......	2,777	......
										4.5	7.4	.0	.1	21.8	.2	1.0	69.5	23.0	......	......	2,610	6.1
										6.0	8.5	.5	.5	17.3	1.4	5.6	66.2	24.8	......	......	2,543	6.1
										7.5	8.1	.3	.5	16.8	1.0	6.2	67.1	24.3	......	......	2,631	......
38	6	87.14	60	.53	103.0	83.3	605	5.9	7.3	1.5	9.1	.0	10.0	2.7	.0	.2	78.0	2.9	......	......	2,631	......
										3.0	7.7	.0	11.7	2.0	.1	.2	78.3	2.3	......	......	2,707	......
										4.5	12.8	.0	.2	12.4	.2	.9	73.5	13.5	......	......	2,476	7.5
										6.0	7.8	.5	.7	18.3	2.2	5.8	64.7	26.8	......	......	2,471	5.7
										7.5	7.8	.7	1.6	15.8	1.8	6.4	65.9	24.7	......	......	2,538	......
55	6	87.91	120	1.09	124.0	102.0	778	6.2	7.6	1.5	7.6	.0	12.0	2.1	.1	.2	78.0	2.4	......	......	2,572	......
										3.0	9.4	.0	10.5	.9	.0	.1	79.1	1.0	......	......	2,718	......
										4.5	14.9	.6	3.3	2.5	.0	.2	78.5	3.3	.002	.000	2,638	10.8
										6.0	14.1	.6	.3	9.2	.1	.4	75.3	10.3	.004	.016	2,671	7.8
										7.5	11.6	.7	.1	12.3	.6	3.0	71.7	16.6	.066	.227	2,536	......

35	12	87.14	54	.13	21.0	15.5	127	6.1	8.2	1.5	10.3	.0	10.1	.4	.0	.1	79.1	.5	....	....	2,318	....
										3.0	16.0	.0	.3	7.3	.1	.3	76.0	7.7	....	....	2,422	....
										4.5	12.3	.0	.1	14.1	.0	.6	72.9	14.7	....	....	2,331	....
										6.0	9.0	.0	.2	19.3	.2	.9	70.4	20.4	....	....	2,316	....
										7.5	7.1	.2	.4	22.3	.3	1.1	68.6	23.9	....	....	2,226	....
										9.0	7.1	.1	.2	22.0	.4	2.3	67.9	24.8	....	....	1,877	....
										10.5	7.1	.6	.2	19.8	.8	5.2	66.3	26.4	....	....	....	5.9
										12.0	9.0	.7	.6	15.9	2.2	4.0	67.6	22.8	....	....	....	6.1
										13.5	9.7	.5	1.3	13.5	1.8	4.4	68.8	20.2	....	....	....	....
57	12	87.91	186	.34	51.9	42.1	213	4.1	5.0	1.5	14.6	.0	5.5	.7	.0	.2	79.0	.9	....	....	2,131	....
										3.0	15.2	.0	3.4	3.1	.0	.2	78.1	3.3	....	....	2,383	....
										4.5	14.7	.0	5.3	.8	.0	.2	79.0	1.0	....	....	2,446	....
										6.0	12.8	.0	1.4	10.6	.1	.4	74.7	11.1	....	....	2,565	....
										7.5	10.0	.0	.0	17.9	.3	.6	71.2	18.8	....	....	2,518	....
										9.0	5.3	.1	.1	25.7	.2	1.3	67.3	27.3	....	....	2,440	....
										10.5	6.6	.5	.1	21.8	1.9	5.0	64.1	29.2	.751	.553	2,034	5.2
										12.0	8.2	.8	.3	16.5	2.5	6.7	65.0	26.5	.945	.477	1,988	5.8
										13.5	7.7	.6	.2	18.5	1.8	6.2	65.0	27.1	.428	.374	1,873	....
47	12	87.14	120	.30	53.0	43.8	255	4.8	5.8	1.5	9.6	.0	10.5	.9	.0	.1	78.9	1.0	....	....	2,559	19.5
										3.0	11.2	.0	8.1	2.5	.0	.4	77.8	2.9	....	....	2,593	14.7
										4.5	14.9	.0	.1	9.3	.1	.2	75.4	9.6	....	....	2,613	8.0
										6.0	8.0	.1	.1	21.1	.1	.5	70.1	21.8	....	....	2,590	6.1
										7.5	5.2	.1	.2	25.0	.1	.8	68.6	26.0	....	....	2,221	5.8
										9.0	4.1	.5	.1	26.2	.7	3.2	65.2	30.6	....	....	2,118	5.3
										10.5	4.1	.7	1.1	23.9	.6	2.9	66.7	28.1	....	....	2,100	5.8
										12.0	7.4	.7	.9	16.9	2.0	6.1	66.0	25.7	....	....	1,980	6.2
										13.5	7.9	.9	1.2	14.9	2.2	6.3	66.6	24.3	....	....	2,104	6.4
34	12	87.14	59	.42	67.0	52.7	387	5.8	7.3	1.5	10.2	.0	8.0	3.9	.1	.2	77.6	4.2	....	....	2,520	....
										3.0	10.8	.0	3.8	9.4	.1	.3	75.6	9.8	....	....	2,529	....
										4.5	12.9	.5	.8	10.0	.0	.4	75.4	10.9	....	....	2,460	....
										6.0	8.3	.5	.2	19.4	.2	.6	70.8	20.7	....	....	2,635	....
										7.5	6.0	.9	.6	22.1	.2	1.3	68.9	24.4	....	....	2,539	....
										9.0	6.0	.5	.2	22.8	.3	3.6	66.6	27.2	....	....	2,460	....
										10.5	3.4	.4	.8	26.1	.6	2.8	65.9	29.9	....	....	2,638	5.5
										12.0	3.8	.7	1.8	23.7	1.8	3.8	64.4	30.0	....	....	2,061	5.4
										13.5	5.2	.7	3.3	17.4	2.0	6.3	65.1	26.5	....	....	2,268	....
36	12	87.14	49	.71	103.0	84.3	495	4.8	5.9	1.5	7.0	.0	13.6	.2	.0	.0	79.2	.2	....	....	2,455	....
										3.0	16.3	.0	3.0	2.6	.0	.1	78.0	2.7	....	....	2,584	....
										4.5	15.1	.0	2.8	4.3	.1	.2	77.5	4.6	....	....	2,752	....
										6.0	8.7	.2	.5	19.5	.2	.6	70.3	20.5	....	....	2,694	....
										7.5	6.7	.6	.2	22.7	.4	.9	68.5	24.6	....	....	2,642	....
										9.0	5.5	.3	.2	24.2	.8	3.1	65.9	28.4	....	....	2,404	....
										10.5	4.2	.5	.1	24.8	.9	4.7	64.8	30.9	....	....	2,361	5.4
										12.0	5.8	.8	.3	20.9	2.2	6.9	63.1	30.8	....	....	2,196	5.4
										13.5	5.6	.8	.2	20.5	2.2	7.4	65.1	30.9	....	....	2,147	....

TABLE 1.—*Results of tests with small experimental furnace.*

PITTSBURGH BITUMINOUS COAL—Continued.

Test No.	Thickness of fuel bed.	Combustible in fuel as fired.	Duration of test.	Pressure in ash pit, inches of water.	Fuel fired per hour.	Combustible burned per hour.	Air forced through fuel bed per hour.	Weight of air per pound of fuel fired, measured with orifice.	Weight of air per pound of combustible, measured with orifice.	Distance of sample from grate.	Average volume composition of gases in fuel bed.								Weight of tar per cubic foot of gas.	Weight of soot per cubic foot of gas.	Temperature in fuel bed.	Weight of air per pound of combustible, computed from gas analysis.
											Carbon dioxide (CO_2).	Unsaturated hydrocarbons.	Oxygen (O_2).	Carbon monoxide (CO).	Methane (CH_4).	Hydrogen (H_2).	Nitrogen (N_2).	Total gaseous combustible.				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	In.	*P. ct.*	*Min.*		*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*In.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*Grams.*	*Grams.*	*°F.*	*Lbs.*
58	12	87.91	151	[a]1.06	105.5	86.5	506	4.9	5.9	1.5	6.5	0.0	14.0	0.6	0.0	0.0	78.9	0.6	......	......	2,417	......
										3.0	14.4	.0	3.4	4.9	.0	.3	77.0	5.2	......	......	2,570	......
										4.5	17.4	.0	1.4	2.9	.0	.2	78.1	3.1	......	......	2,556	......
										6.0	13.6	.0	.4	11.3	.0	.5	74.2	11.8	......	......	2,584	......
										7.5	13.9	.0	.6	10.2	.0	.6	74.7	10.8	......	......	2,748	......
										9.0	11.0	.0	.1	15.8	.2	.9	72.0	16.9	......	......	2,509	......
										10.5	8.4	.1	.1	19.8	.3	2.4	68.9	22.6	0.061	0.137	2,442	6.1
										12.0	7.0	.7	.3	18.1	2.0	7.6	64.3	28.4	.658	.738	2,496	5.8
										13.5	8.6	.7	.2	16.5	1.7	6.6	65.7	25.5	.311	.541	2,620	......
37	12	87.14	58	.71	114.0	91.5	605	5.3	6.6	1.5	5.6	.0	14.6	.8	.0	.1	78.9	.9	......	......	2,592	......
										3.0	6.0	.0	15.4	.4	.0	.1	79.1	.5	......	......	2,646	......
										4.5	12.7	.0	6.5	2.3	.0	.2	78.3	2.5	......	......	2,602	......
										6.0	11.6	.0	.4	14.5	.1	.3	73.1	14.9	......	......	2,682	......
										7.5	9.1	.1	.3	18.4	.2	.7	71.2	19.4	......	......	2,608	......
										9.0	7.9	.1	.2	20.3	.3	1.7	69.5	22.4	......	......	2,566	......
										10.5	4.7	.8	1.0	21.1	.6	3.9	67.9	26.4	......	......	2,480	6.3
										12.0	6.9	.6	1.3	17.0	2.2	7.2	64.8	27.0	......	......	2,433	6.1
										13.5	8.0	.6	.3	16.9	1.6	7.1	65.5	26.2	......	......	2,419	......
56	12	87.91	153	1.33	130.8	111.5	765	5.9	6.9	1.5	.5	.0	20.2	.1	.0	.0	79.2	.1	......	......	2,282	......
										3.0	6.4	.0	13.8	.7	.0	.1	79.0	.8	......	......	2,417	......
										4.5	9.4	.0	10.8	.8	.0	.1	78.9	.9	......	......	2,602	......
										6.0	12.5	.0	6.4	2.5	.0	.2	78.4	2.7	......	......	2,541	......
										7.5	14.6	.0	2.0	6.6	.1	.2	76.5	6.9	......	......	2,484	......
										9.0	8.3	.1	.0	20.5	.1	1.5	69.5	22.2	......	......	2,486	......
										10.5	9.2	.1	.0	18.3	.6	4.8	67.0	23.8	.148	.198	2,539	6.1
										12.0	12.6	.1	.2	12.8	.2	1.3	72.8	14.4	.055	.092	2,198	7.2
										13.5	8.6	.3	.0	19.3	.8	3.5	67.5	23.9	.147	.349	2,370	......

59	12	87.91	63	2.1	184.8	157.0	1,115	6.0	7.1	1.5	1.9	.0	18.8	.3	.0	.0	79.0	.3	......	......	2,280	......
										3.0	3.9	.0	16.8	.3	.0	.0	79.0	.3	......	......	2,628	......
										4.5	5.6	.0	15.0	.3	.0	.0	79.1	.3	......	......	2,847	......
										6.0	12.5	.0	7.8	.5	.0	.1	79.1	.6	......	......	2,635	......
										7.5	15.9	.0	3.7	1.6	.1	.1	78.6	1.8	......	......	2,700	......
										9.0	16.1	.1	.6	6.6	.0	.3	76.3	7.0	......	......	2,484	......
										10.5	14.5	.1	1.0	8.3	.1	1.3	74.7	9.8	.017	.118	2,550	8.3
										12.0	12.9	.1	.1	11.0	.6	3.2	72.1	14.9	.123	.415	2,410	7.5
										13.5	8.3	.6	1.3	14.7	1.2	7.8	66.1	24.3	.369	.976	2,439	......

ANTHRACITE COAL.

20	6	83.56	69	0.15	20.0	13.7	120	6.0	8.7	1.5	14.8	......	4.9	1.4	0.0	0.1	78.8	1.6	......	......	2,316	......
										3.0	14.8	......	.1	9.6	.1	.6	74.8	10.3	......	......	2,203	......
										4.5	12.5	......	.5	12.3	.2	2.2	72.3	14.7	......	......	1,897	8.1
										6.0	10.1	......	1.2	14.0	.4	4.7	69.6	19.1	......	......	......	8.0
										7.5	11.2	......	3.9	6.6	.2	2.5	75.6	9.3	......	......	......	......
44	6	86.90	48	.16	20.0	14.9	142	7.0	9.5	1.5	13.5	......	6.7	.9	.0	.1	78.8	1.0	......	......	2,206	......
										3.0	17.7	......	.8	3.9	.0	.2	77.4	4.1	......	......	2,376	......
										4.5	16.5	......	.0	6.8	.1	.5	76.1	7.4	......	......	2,093	9.2
										6.0	11.0	......	.4	14.1	.2	2.8	71.5	17.1	......	......	1,920	8.0
										7.5	11.7	......	3.7	6.8	.1	1.7	76.0	8.6	......	......	1,785	......
63	6	85.11	140	.29	30.0	20.7	178	5.9	8.6	1.5	17.0	......	2.8	.9	.1	.3	78.9	1.3	......	......	2,431	......
										3.0	15.8	......	2.6	3.4	.0	.4	77.8	3.8	......	......	2,419	......
										4.5	11.9	......	2.4	10.3	.0	1.0	74.4	11.3	......	......	2,215	9.5
										6.0	7.7	......	.0	20.2	.4	6.4	65.3	27.0	......	......	1,720	6.6
										7.5	9.1	......	.0	17.1	.4	6.6	66.8	24.1	......	......	......	......
21	6	83.56	60	.46	40.0	29.8	246	6.1	8.3	1.5	16.4	......	1.6	4.5	.1	.2	77.2	4.8	......	......	2,208	......
										3.0	14.4	......	1.0	8.5	.1	.3	75.7	8.9	......	......	2,404	......
										4.5	11.5	......	2.0	11.4	.2	.4	74.5	12.0	......	......	2,412	9.1
										6.0	6.2	......	1.3	20.8	.4	3.7	67.6	24.9	......	......	2,334	7.0
										7.5	7.0	......	.7	19.0	.6	6.2	66.5	25.8	......	......	1,850	......
43	6	86.90	60	.81	60.0	47.9	382	6.4	8.0	1.5	14.5	......	4.9	2.0	.0	.1	78.5	2.1	......	......	2,491	13.4
										3.0	13.3	......	.0	12.3	.0	.5	73.9	12.8	......	......	2,615	8.1
										4.5	9.5	......	.0	18.4	.1	.8	71.2	19.3	......	......	2,521	7.2
										6.0	5.7	......	.0	24.3	.2	2.9	66.9	27.4	......	......	2,419	6.2
										7.5	6.3	......	.1	22.4	.5	4.0	66.7	26.9	......	......	1,974	6.4
23	6	83.56	55	1.30	74.0	54.7	516	7.1	9.5	1.5	14.9	......	1.0	7.8	.2	.3	75.8	8.3	......	......	2,289	......
										3.0	12.1	......	1.3	12.1	.1	.4	74.0	12.6	......	......	2,293	......
										4.5	7.8	......	1.9	18.3	.1	.6	71.3	19.0	......	......	2,376	7.7
										6.0	9.4	......	.3	17.9	.2	.7	71.5	18.8	......	......	2,442	7.3
										7.5	8.5	......	.6	18.3	.4	2.7	69.5	21.4	......	......	2,440	......

[a] About two-thirds of grate area covered with clinker.

TABLE 1.—*Results of tests with small experimental furnace*.—Continued.

ANTHRACITE COAL—Continued.

Test No.	Thickness of fuel bed.	Combustible in fuel as fired.	Duration of test.	Pressure in ash pit, inches of water.	Fuel fired per hour.	Combustible burned per hour.	Air forced through fuel bed per hour.	Weight of air per pound of fuel fired, measured with orifice.	Weight of air per pound of combustible, measured with orifice.	Distance of sample from grate.	Average volume composition of gases in fuel bed.								Weight of tar per cubic foot of gas.	Weight of soot per cubic foot of gas.	Temperature in fuel bed.	Weight of air per pound of combustible, computed from gas analysis.
											Carbon dioxide (CO_2).	Unsaturated hydrocarbons.	Oxygen (O_2).	Carbon monoxide (CO).	Methane (CH_4).	Hydrogen (H_2).	Nitrogen (N_2).	Total gaseous combustible.				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	In.	*P. ct.*	*Min.*		*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*In.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*Grams.*	*Grams.*	*° F.*	*Lbs.*
24	6	83.56	60	2.20	100.0	75.0	675	6.8	9.0	1.5	11.2	....	5.8	6.1	0.0	0.1	76.8	6.2	....	....	2,340	....
										3.0	9.8	....	1.6	15.2	.0	.3	73.1	15.5	....	....	2,306	....
										4.5	6.2	....	.8	22.4	.2	.8	69.6	23.4	....	....	2,426	6.8
										6.0	5.1	....	1.2	23.7	.2	2.0	67.8	25.9	....	....	2,478	6.6
										7.5	3.5	....	2.1	23.5	.2	2.8	67.9	26.5	....	....	2,638	....
45	12	85.11	90	.27	20.0	13.1	140	7.0	10.7	1.5	6.4	....	13.8	.9	.0	.1	78.8	1.0	....	....	2,266	....
										3.0	16.3	....	1.8	4.0	.0	.2	77.7	4.2	....	....	2,347	....
										4.5	14.8	....	.0	9.7	.0	.3	75.2	10.0	....	....	2,215	....
										6.0	9.0	....	.2	19.4	.0	.5	70.9	19.9	....	....	2,142	....
										7.5	8.2	....	.1	20.5	.2	.6	70.4	21.3	....	....	2,071	....
										9.0	6.2	....	.1	23.5	.1	1.4	68.7	25.0	....	....	2,052	....
										10.5	4.4	....	.6	25.2	.1	2.9	66.8	28.2	....	....	1,792	6.4
										12.0	6.0	....	.4	21.9	.4	4.0	67.3	26.3	....	....	....	6.7
										13.5	8.1	....	1.2	16.6	.4	4.2	69.5	21.2	....	....	....	....
62	12	85.11	180	.20	20.0	15.5	113	5.7	7.3	1.5	7.5	....	12.8	.5	.0	.2	79.0	.7	....	....	2,386	....
										3.0	16.8	....	.1	6.4	.1	.7	75.9	7.2	....	....	2,415	....
										4.5	14.2	....	.0	10.9	.0	1.3	73.6	12.2	....	....	2,341	....
										6.0	12.4	....	.0	14.3	.0	1.7	71.6	16.0	....	....	2,287	....
										7.5	11.1	....	.0	16.2	.0	1.9	70.8	18.1	....	....	1,852	....
										9.0	9.7	....	.0	18.3	.0	2.6	69.4	20.9	....	....	1,983	....
										10.5	5.1	....	.0	25.1	.1	5.7	64.0	30.9	....	....	....	6.0
										12.0	9.7	....	.6	15.6	.1	5.3	68.7	21.0	....	....	....	7.7
										13.5	9.4	....	1.3	14.3	.3	6.0	68.7	20.6	....	....	....	....

32	12	86.90	71	.12	21.2	16.7	130	6.1	7.8	1.5	4.9	....	15.3	.9	.0	.0	78.9	.9	....	....	2,327	....
										3.0	12.0	....	6.7	2.5	.1	.0	78.7	2.6	....	....	2,392	....
										4.5	17.0	....	2.5	1.6	.0	.0	78.9	1.6	....	....	2,287	....
										6.0	13.9	....	.0	11.0	.0	.6	74.5	11.6	....	....	2,170	....
										7.5	12.2	....	.0	13.8	.1	.9	73.0	14.8	....	....	2,124	....
										9.0	11.1	....	.0	14.9	.2	2.6	71.2	17.7	....	....	1,902	....
										10.5	10.2	....	.5	13.6	.4	8.1	67.2	22.1	....	....	....	6.8
										12.0	9.7	....	4.3	7.2	.4	3.8	74.6	11.4	....	....	....	12.2
										13.5	9.9	....	5.1	6.0	.3	2.3	76.4	8.6	....	....	....	....
26	12	83.56	69	.65	40	28.9	251	6.3	8.6	1.5	9.6	....	10.7	.7	.1	.0	78.9	.8	....	....	2,354	....
										3.0	13.4	....	6.2	1.3	.1	.1	78.9	1.5	....	....	2,349	....
										4.5	13.0	....	.7	11.9	.1	.6	73.7	12.6	....	....	2,253	....
										6.0	10.5	....	1.4	15.0	.1	.9	72.1	16.0	....	....	2,287	....
										7.5	10.0	....	1.4	15.4	.2	.8	72.2	16.4	....	....	2,453	....
										9.0	8.7	....	.7	18.6	.2	1.1	70.7	19.9	....	....	2,188	....
										10.5	6.0	....	1.0	22.8	.2	1.9	68.1	24.9	....	....	1,810	6.6
										12.0	5.2	....	1.1	23.4	.3	3.3	66.7	27.0	....	....	1,700	6.3
										13.5	6.6	....	1.9	18.1	.6	6.1	66.7	24.8	....	....	....	....
29	12	86.9	63	1.36	60	46.1	368	6.2	8.0	1.5	14.8	....	4.3	2.6	.0	0.2	78.1	2.8	....	....	2,350	....
										3.0	16.4	....	.3	6.5	.0	.2	76.6	6.7	....	....	2,356	....
										4.5	14.8	....	.2	9.1	.1	.2	75.6	9.4	....	....	2,347	....
										6.0	....	....	(a)	(a)	(a)	(a)	(a)	(a)	....	....	2,449	....
										7.5	14.5	....	1.6	7.3	.0	.2	76.4	7.5	....	....	2,629	....
										9.0	14.2	....	.2	10.3	.0	.2	75.1	10.5	....	....	2,527	....
										10.5	8.9	....	.0	19.2	.1	1.4	70.4	20.7	....	....	2,338	7.1
										12.0	6.4	....	.1	22.2	.3	4.4	66.6	26.9	....	....	....	6.5
										13.5	8.5	....	.6	16.8	.5	6.4	67.2	23.7	....	....	....	....
33	12	86.9	66	1.74	60	50.7	450	7.5	8.9	1.5	12.3	....	7.1	2.1	.0	.0	78.5	2.1	....	....	2,464	15.4
										3.0	14.5	....	4.5	2.2	.0	.1	78.7	2.3	....	....	2,561	13.3
										4.5	15.5	....	.2	7.4	.1	.2	76.6	7.7	....	....	2,622	9.4
										6.0	12.6	....	.1	12.3	.1	.3	74.6	12.7	....	....	2,658	8.4
										7.5	10.8	....	.1	15.6	.1	.4	73.0	16.1	....	....	2,806	7.8
										9.0	8.4	....	.0	20.0	.1	.5	71.0	20.6	....	....	2,817	7.0
										10.5	3.8	....	.0	28.0	.2	1.1	66.9	29.3	....	....	2,592	5.9
										12.0	2.5	....	.3	28.9	.2	2.9	65.2	32.0	....	....	2,268	5.8
										13.5	5.2	....	.1	23.1	.3	6.4	64.9	29.8	....	....	1,828	6.4
30	12	86.9	60	2.36	78	64.9	505	6.5	7.8	1.5	5.9	....	14.0	1.1	.0	.0	79.0	1.1	....	....	2,518	....
										3.0	15.7	....	2.7	3.7	.0	.0	77.9	3.7	....	....	2,658	....
										4.5	11.2	....	.0	15.8	.0	.2	72.8	16.0	....	....	2,521	....
										6.0	10.1	....	.1	17.5	.1	.7	71.5	18.3	....	....	2,692	....
										7.5	9.1	....	.2	19.2	.2	.6	70.7	20.0	....	....	2,766	....
										9.0	6.0	....	.0	24.4	.2	1.0	68.4	25.6	....	....	2,595	....
										10.5	4.3	....	.0	27.0	.2	1.9	66.6	29.1	....	....	2,446	6.0
										12.0	3.6	....	.2	27.6	.2	2.7	65.7	30.5	....	....	2,064	5.9
										13.5	6.4	....	.1	21.1	.5	7.2	64.7	28.8	....	....	....	....

[a] Air leak.

TABLE 1.—*Results of tests with small experimental furnace*—Continued.

ANTHRACITE COAL—Continued.

Test No.	Thickness of fuel bed.	Combustible in fuel as fired.	Duration of test.	Pressure in ash pit, inches of water.	Fuel fired per hour.	Combustible burned per hour.	Air forced through fuel bed per hour.	Weight of air per pound of fuel fired, measured with orifice.	Weight of air per pound of combustible, measured with orifice.	Distance of sample from grate.	Average volume composition of gases in fuel bed.								Weight of tar per cubic foot of gas.	Weight of soot per cubic foot of gas.	Temperature in fuel bed.	Weight of air per pound of combustible, computed from gas analysis.
											Carbon dioxide (CO₂).	Unsaturated hydro-carbons.	Oxygen (O₂).	Carbon monoxide (CO).	Methane (CH₄).	Hydrogen (H₂).	Nitrogen (N₂).	Total gaseous com-bustible.				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	In.	*P. ct.*	*Min.*		*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*Lbs.*	*In.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*Grams.*	*Grams.*	° *F.*	*Lbs.*
31	12	86.9	44	2.83	99.5	80.2	645	6.5	8.1	1.5	10.9	....	9.0	0.9	.0	0.0	79.2	0.9	....	....	2,595	....
										3.0	15.7	....	4.1	1.2	.0	.1	78.9	1.3	....	....	2,615	....
										4.5	16.1	....	1.1	5.2	.0	.3	77.3	5.5	....	....	2,694	....
										6.0	8.6	....	.0	20.0	.0	.7	70.7	20.7	....	....	2,635	....
										7.5	7.9	....	.1	21.0	.1	.7	70.2	21.8	....	....	2,622	....
										9.0	5.9	....	.0	24.4	.1	1.4	68.2	25.9	....	....	2,640	....
										10.5	4.8	....	.0	26.4	.0	2.8	66.0	29.2	....	....	2,338	6.0
										12.0	4.0	....	.2	26.8	.2	3.8	65.0	30.8	....	....	2,259	5.9
										13.5	5.8	....	.1	22.1	.4	8.6	63.0	31.1	....	....	....	....

COKE.

Test No.	Thickness of fuel bed.	Combustible in fuel as fired.	Duration of test.	Pressure in ash pit, inches of water.	Fuel fired per hour.	Combustible burned per hour.	Air forced through fuel bed per hour.	Weight of air per pound of fuel fired, measured with orifice.	Weight of air per pound of combustible, measured with orifice.	Distance of sample from grate.	Carbon dioxide (CO₂).	Unsaturated hydro-carbons.	Oxygen (O₂).	Carbon monoxide (CO).	Methane (CH₄).	Hydrogen (H₂).	Nitrogen (N₂).	Total gaseous com-bustible.	Weight of tar per cubic foot of gas.	Weight of soot per cubic foot of gas.	Temperature in fuel bed.	Weight of air per pound of combustible, computed from gas analysis.
48	6	81.85	75	0.07	20.0	15.1	138	6.9	9.2	1.5	6.2	....	14.1	0.6	0.0	0.2	78.9	0.8	....	....	2,341	....
										3.0	14.1	....	6.1	.6	.0	.2	79.0	.8	....	....	2,377	....
										4.5	17.6	....	2.2	1.2	.1	.2	78.7	1.5	....	....	2,460	12.1
										6.0	14.0	....	.0	11.2	.1	.3	74.4	11.6	....	....	2,251	8.6
										7.5	14.3	....	.3	9.8	.1	.3	75.2	10.2	....	....	1,789	....
										9.0	....	....	....	....	....	....	....	....	....	....	1,780	....
40	6	82.68	38	.15	38.0	29.0	248	6.5	8.5	1.5	4.9	....	15.6	.3	.0	.0	79.2	.3	....	....	2,521	....
										3.0	16.8	....	3.2	1.1	.0	.1	78.8	1.2	....	....	2,615	....
										4.5	16.1	....	.0	7.6	.0	.3	76.0	7.9	....	....	2,426	9.4
										6.0	10.5	....	.0	16.8	.0	.9	71.8	17.7	....	....	2,127	7.7
										7.5	12.2	....	.2	13.5	.0	.9	73.2	14.4	....	....	1,854	....

50	6	81.85	120	.40	51.0	36.7	367	7.2	10.0	1.5	5.4	......	15.3	.2	.0	.0	79.1	.2	......	......	2,619	41.1
										3.0	14.7	......	5.4	.9	.0	.1	78.9	1.0	......	......	2,620	14.7
										4.5	17.9	......	1.3	2.2	.0	.2	78.4	2.4	......	......	2,543	11.3
										6.0	11.3	......	.0	14.7	.0	.7	73.3	15.4	......	......	2,523	8.2
										7.5	11.4	......	.0	15.3	.1	.7	72.5	16.1	......	......	2,232	7.9
										9.0	......	......	......	......	......	......	......	......	......	......	2,021	......
41	6	82.68	38	.55	71	55.7	505	7.1	9.2	1.5	5.2	......	15.2	.5	.0	.0	79.1	.5	......	......	2,516	......
										3.0	13.0	......	7.4	.4	.0	.0	79.2	.4	......	......	2,732	......
										4.5	16.6	......	.1	6.3	.0	.2	76.8	6.5	......	......	2,716	9.8
										6.0	10.3	......	.1	17.4	.0	.5	71.7	17.9	......	......	2,628	7.6
										7.5	10.0	......	.2	17.6	.1	.6	71.5	18.3	......	......	2,383	......
										9.0	......	......	......	......	......	......	......	......	......	......	2,194	......
61	6	81.85	70	1.02	99.4	72.9	770	7.7	10.6	1.5	5.6	......	14.7	.4	.0	.1	79.2	.5	......	......	2,667	......
										3.0	12.9	......	7.2	.5	.0	.0	79.4	.5	......	......	2,829	......
										4.5	18.2	......	1.0	2.0	.0	.2	78.6	2.2	......	......	2,957	11.3
										6.0	14.5	......	.4	9.7	.1	.7	74.6	10.5	......	......	2,631	8.9
										7.5	13.4	......	.0	12.0	.1	.8	73.7	12.9	......	......	2,394	......
										9.0	......	......	......	......	......	......	......	......	......	......	2,396	......
42	6	82.68	34	1.20	106	79	740	6.9	9.3	1.5	2.0	......	18.5	.4	.0	.0	79.1	.4	......	......	2,588	......
										3.0	9.8	......	10.2	.9	.0	.0	79.1	.9	......	......	2,633	......
										4.5	16.3	......	3.7	.7	.0	.1	79.2	.8	......	......	2,703	13.6
										6.0	11.3	......	.0	15.5	.0	.2	73.0	15.7	......	......	2,748	7.9
										7.5	9.8	......	.2	17.6	.0	.4	72.0	18.0	......	......	2,590	......
										9.0	......	......	......	......	......	......	......	......	......	......	2,363	......
19	12	82.68	88	.05	15.0	10.6	100	6.7	9.5	1.5	6.4	......	14.1	.2	.0	.0	79.3	.2	......	......	2,062	......
										3.0	12.4	......	8.1	.4	.0	.0	79.1	.4	......	......	2,142	......
										4.5	15.7	......	3.0	3.4	.1	.1	77.7	3.6	......	......	2,115	......
										6.0	......	......	(a)	(a)	(a)	(a)	(a)	(a)	......	......	1,870	......
										7.5	14.7	......	.5	9.3	.2	.4	74.9	9.9	......	......	1,807	......
										9.0	......	......	(a)	(a)	(a)	(a)	(a)	(a)	......	......	......	......
										10.5	9.6	......	.4	17.6	.3	.5	71.6	18.4	......	......	......	7.6
										12.0	9.7	......	7.0	6.3	.1	.2	76.7	6.6	......	......	......	13.9
										13.5	8.2	......	11.5	1.4	.0	.1	78.8	1.5	......	......	......	......
15	12	82.68	90	.11	19.3	13.5	140	7.3	10.3	1.5	7.1	......	13.4	.4	.0	.0	79.1	.4	......	......	2,233	......
										3.0	12.2	......	7.8	.8	.0	.0	79.2	.8	......	......	2,376	......
										4.5	16.4	......	1.9	3.5	.0	.2	78.0	3.7	......	......	2,278	......
										6.0	14.1	......	.6	9.9	.2	.2	75.0	10.3	......	......	2,109	......
										7.5	10.6	......	.5	15.6	.1	.6	72.6	16.3	......	......	2,010	......
										9.0	8.8	......	.5	18.5	.1	.6	71.5	19.2	......	......	1,758	......
										10.5	8.5	......	1.0	18.7	.1	.8	70.9	19.6	......	......	......	7.6
										12.0	9.6	......	.6	17.7	.2	.5	71.4	18.4	......	......	......	7.6
										13.5	11.6	......	1.6	12.5	.2	.5	73.6	13.2	......	......	......	......

[a] Air leak.

TABLE 1.—*Results of tests with small experimental furnace*—Continued.

COKE—Continued.

Test No.	Thickness of fuel bed.	Combustible in fuel as fired.	Duration of test.	Pressure in ash pit, inches of water.	Fuel fired per hour.	Combustible burned per hour.	Air forced through fuel bed per hour.	Weight of air per pound of fuel fired, measured with orifice.	Weight of air per pound of combustible, measured with orifice.	Distance of sample from grate.	Average volume composition of gases in fuel bed.								Weight of tar per cubic foot of gas.	Weight of soot per cubic foot of gas.	Temperature in fuel bed.	Weight of air per pound of combustible, computed from gas analysis.
											Carbon dioxide (CO_2).	Unsaturated hydrocarbons.	Oxygen (O_2).	Carbon monoxide (CO).	Methane (CH_4).	Hydrogen (H_2).	Nitrogen (N_2).	Total gaseous combustible.				
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
	In.	P. ct.	Min.		Lbs.	Lbs.	Lbs.	Lbs.	Lbs.	In.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	P. ct.	Grams.	Grams.	° F.	Lbs.
51	12	81.85	177	0.09	19.7	15.4	129	6.5	8.4	1.5	5.7	....	14.6	0.7	0.0	0.1	78.9	0.8	....	....	2,165	....
										3.0	7.2	....	13.3	.3	.0	.1	79.1	.4	....	....	2,329	....
										4.5	14.0	....	6.2	.6	.0	.1	79.1	.7	....	....	2,437	....
										6.0	15.5	....	.0	8.5	.1	.3	75.6	8.9	....	....	2,395	....
										7.5	12.0	....	.0	14.3	.0	.6	73.1	14.9	....	....	2,212	....
										9.0	9.7	....	.0	18.2	.1	.6	71.4	18.9	....	....	2,160	....
										10.5	6.1	....	.0	24.6	.1	1.1	68.1	25.8	....	....	1,722	06.4
										12.0	7.7	....	.0	21.4	.1	1.2	69.6	22.7	....	....	....	6.9
										13.5	10.6	....	1.3	14.2	.1	.8	73.0	15.1	....	....	....	....
49	12	81.85	87	.11	20	15.6	133	6.7	8.5	1.5	7.8	....	12.5	.6	.0	.0	79.1	.6	....	....	2,394	....
										3.0	16.6	....	3.7	.7	.0	.1	78.9	.8	....	....	2,467	....
										4.5	15.7	....	4.3	1.1	.0	.1	78.8	1.2	....	....	2,523	....
										6.0	13.7	....	.1	11.5	.0	.3	74.4	11.8	....	....	2,496	....
										7.5	10.4	....	.1	16.6	.1	.4	72.4	17.1	....	....	2,421	....
										9.0	9.9	....	.0	17.4	.0	.6	72.1	18.0	....	....	2,190	....
										10.5	6.4	....	.0	23.9	.0	1.0	68.7	24.9	....	....	1,765	6.6
										12.0	8.2	....	.3	20.0	.0	1.1	70.4	21.1	....	....	1,675	7.3
										13.5	11.6	....	1.6	11.9	.0	.7	74.2	12.6	....	....	....	....
18	12	82.68	67	.18	41.2	32.1	259	6.3	8.1	1.5	5.4	....	15.2	.6	.0	.1	78.7	.7	....	....	2,248	....
										3.0	9.1	....	11.5	.3	.0	.0	79.1	.3	....	....	2,323	....
										4.5	16.9	....	3.0	1.4	.0	.1	78.6	1.5	....	....	2,496	....
										6.0	....	....	(a)	(a)	(a)	(a)	(a)	(a)	....	....	2,469	....
										7.5	10.8	....	.1	16.6	.2	.3	72.0	17.1	....	....	2,244	....
										9.0	7.7	....	1.2	19.6	.2	.5	70.8	20.3	....	....	1,834	....
										10.5	6.6	....	.5	22.5	.2	.7	69.5	23.4	....	....	1,702	6.9
										12.0	7.1	....	.0	22.6	.2	1.0	69.1	23.8	....	....	....	6.7
										13.5	9.3	....	.1	18.7	.2	.9	70.8	19.8	....	....	....	....

16	12	82.68	55	.52	62	46.6	380	6.1	8.2	1.5	7.6	....	12.7	.9	.0	.1	78.7	1.0	....	....	2,494	26.1
										3.0	14.6	....	4.4	2.4	.0	.0	78.6	2.4	....	....	2,575	13.0
										4.5	17.2	....	1.6	2.7	.0	.0	78.5	2.7	....	....	2,678	11.1
										6.0	10.9	....	.0	15.8	.1	.3	72.9	16.1	....	....	2,374	7.7
										7.5	11.6	....	.0	14.7	.1	.2	73.4	15.0	....	....	2,239	7.8
										9.0	8.6	....	.0	20.0	.1	.5	70.8	20.6	....	....	2,014	7.0
										10.5	4.9	....	.4	26.0	.1	.6	68.0	26.7	....	....	1,944	6.4
										12.0	4.7	....	.1	26.8	.1	.5	67.8	27.4	....	....	1,873	6.3
										13.5	7.3	....	.6	21.2	.2	.8	69.9	22.2	....	....	1,591	6.9
14	12	82.68	62	1.01	81.4	61.4	556	6.8	9.1	1.5	3.5	....	17.0	.5	.0	.0	79.0	.5	....	....	2448	....
										3.0	8.8	....	11.5	.6	.0	.0	79.1	.6	....	....	2527	....
										4.5	11.1	....	9.4	.1	.0	.0	79.4	.1	....	....	2642	....
										6.0	15.4	....	2.2	5.0	.0	.0	77.4	5.0	....	....	2626	....
										7.5	14.5	....	.8	8.7	.0	.2	75.8	8.9	....	....	2595	....
										9.0	10.9	....	1.1	14.4	.1	.3	73.2	14.8	....	....	2386	....
										10.5	5.9	....	.2	24.5	.2	.4	68.8	25.1	....	....	2444	6.6
										12.0	6.4	....	.1	23.9	.1	.6	68.9	24.6	....	....	2221	6.6
										13.5	8.8	....	.8	18.5	.1	.4	71.4	19.0	....	....	1859	....
17	12	82.68	50	1.10	104.3	79.0	698	6.7	8.8	1.5	5.9	....	14.7	.6	.0	.0	78.8	.6	....	....	2424	....
										3.0	9.0	....	11.4	.7	.0	.0	78.9	.7	....	....	2586	....
										4.5	15.4	....	4.3	1.5	.0	.0	78.8	1.5	....	....	2669	....
										6.0	....	....	(a)	(a)	(a)	(a)	(a)	(a)	....	....	2545	....
										7.5	13.3	....	.5	11.4	.1	.3	74.4	11.8	....	....	2624	....
										9.0	10.6	....	.5	16.1	.2	.5	72.1	16.8	....	....	2471	....
										10.5	6.9	....	.0	23.2	.1	.8	69.0	24.1	....	....	2302	6.7
										12.0	7.3	....	.2	22.4	.1	.7	69.3	23.2	....	....	2235	6.8
										13.5	8.5	....	.5	19.4	.1	.7	70.8	20.2	....	....	1852	....
60	12	81.85	90	1.67	118.6	88.3	756	6.4	8.6	1.5	2.7	....	17.6	0.8	.0	.1	78.8	.9	....	....	2500	....
										3.0	5.4	....	15.1	0.4	.0	.1	79.0	.5	....	....	2784	....
										4.5	10.0	....	10.5	0.1	.0	.1	79.3	.2	....	....	2917	....
										6.0	16.4	....	2.2	3.2	.0	.2	78.0	3.4	....	....	2826	....
										7.5	16.2	....	.1	7.1	.0	.3	76.3	7.4	....	....	2818	....
										9.0	12.2	....	.2	13.8	.1	.6	73.1	14.5	....	....	2800	....
										10.5	9.7	....	.0	18.3	.1	.8	71.1	19.2	....	....	2845	7.4
										12.0	8.4	....	.0	20.7	.1	1.0	69.8	21.8	....	....	2656	7.0
										13.5	8.4	....	.0	20.4	.1	1.1	70.0	21.6	....	....	2165	....

[a] Air leak.

DISCUSSION OF RESULTS OF TESTS.

The results of the tests made with the experimental furnace can be studied best by means of charts. For this purpose the charts given in figures 8 to 18 have been prepared. The notation and the legend at the bottom of each chart give complete information as to what the chart contains, so that each one can be studied without reference to

COMPOSITION OF GASES IN THE FUEL BED.

Figures 8 to 13, inclusive, show the composition of gases and the temperature at various depths in the fuel bed. The gases O_2 and CO_2 are represented by their chemical symbols. The "total combustible" curve shows the sum of the percentages of total gaseous combustible ($CO+CH_4+H_2+$unsaturated hydrocarbons). The important fact shown by the charts is that with a 6-inch bed of Pittsburgh or anthracite coal the oxygen is all used up in combustion at a distance of 3 to 4½ inches above the grate. The CO_2 content reaches a maximum of about 15 per cent at a distance of 2 to 3 inches above the grate and then decreases until at the surface of the fuel bed it is 7 to 10 per cent. The percentage of combustible in the gases increases rapidly beyond 3 inches above the grate. At the surface of the fuel bed there is 20 to 32 per cent of combustible in the gases, and practically no oxygen. The temperatures vary from 1,120 to 1,500° C. (2,012 to 2,732° F.). The maximum temperature is at about the same height in the fuel bed as the maximum percentage of CO_2.

With 12-inch beds of all three fuels and with a 6-inch bed of coke, all of the oxygen disappears 4½ to 6 inches above the grate. The points of maximum CO_2 content and maximum temperature are also somewhat higher from the grate in the coke fuel bed than in the 6-inch fuel beds with Pittsburgh and anthracite coal. However, in all the tests there was at the surface of the fuel bed a large percentage of combustible gas and no oxygen to burn it, showing that the fuel bed of any hand-fired furnace acts primarily as a gas producer. In many tests the gas at the surface of the fuel bed would be considered a fairly good grade of producer gas.

The irregularities in the curves for the tests made at high rates of combustion are due to cavities formed in the fuel bed. The narrow space between opposite walls of the furnace caused the fuel to bridge over. In addition to this the gas samplers, which were inserted radially, formed a support for the fuel and prevented it from sliding down easily. Thus cavities were formed in the fuel bed which allowed the air to penetrate a greater distance above the grate before the oxygen was used up in combustion. With high rates of combustion the fuel under the samplers burned out so fast that even frequent poking could not prevent the formation of cavities.

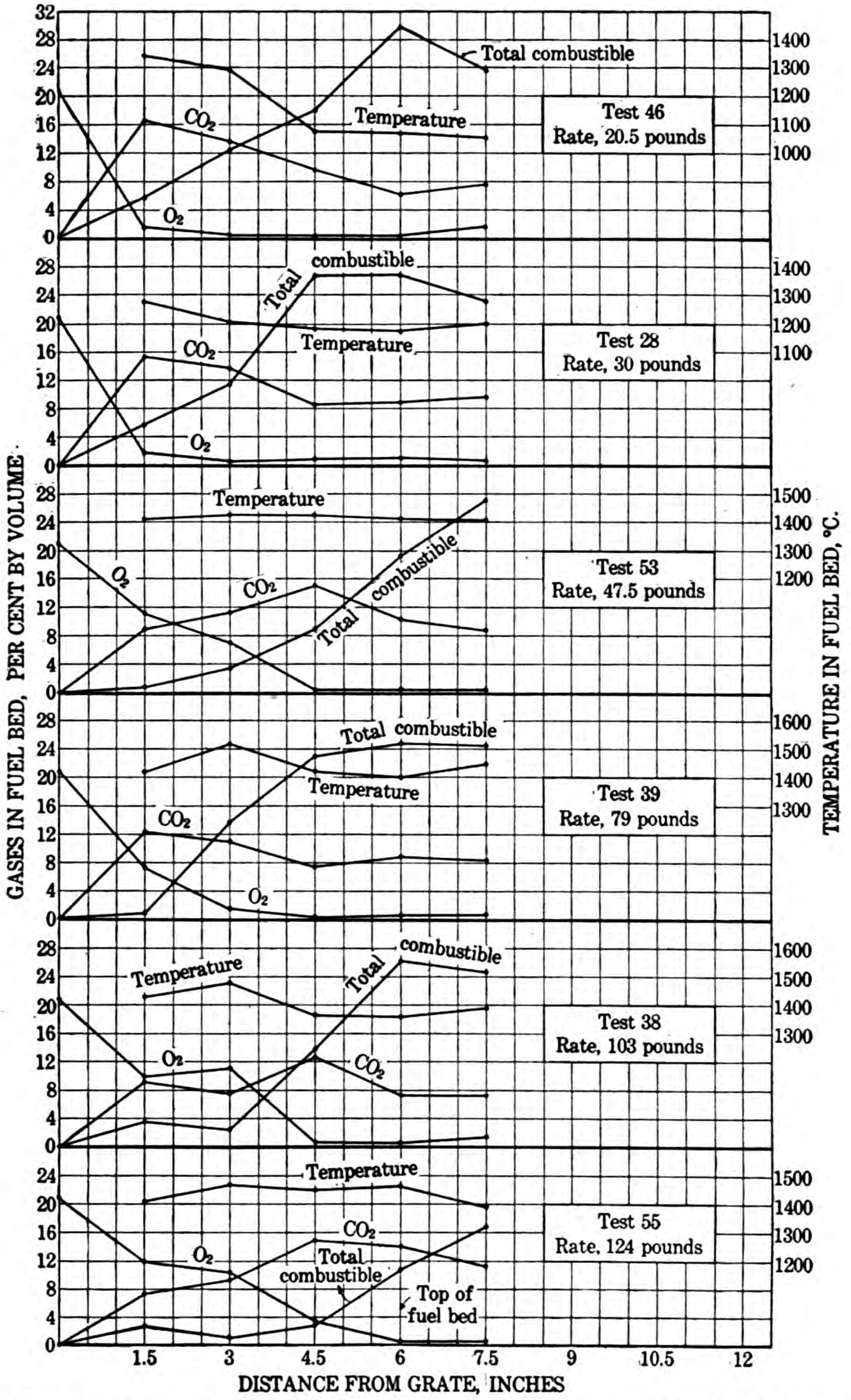


FIGURE 8.—Composition of gases and temperature in 6-inch fuel bed of Pittsburgh bituminous coal in a small hand-fired experimental furnace. Rates of combustion, 20.5, 30, 47.5, 79, 103, and 124 pounds of fuel per square foot of grate per hour.

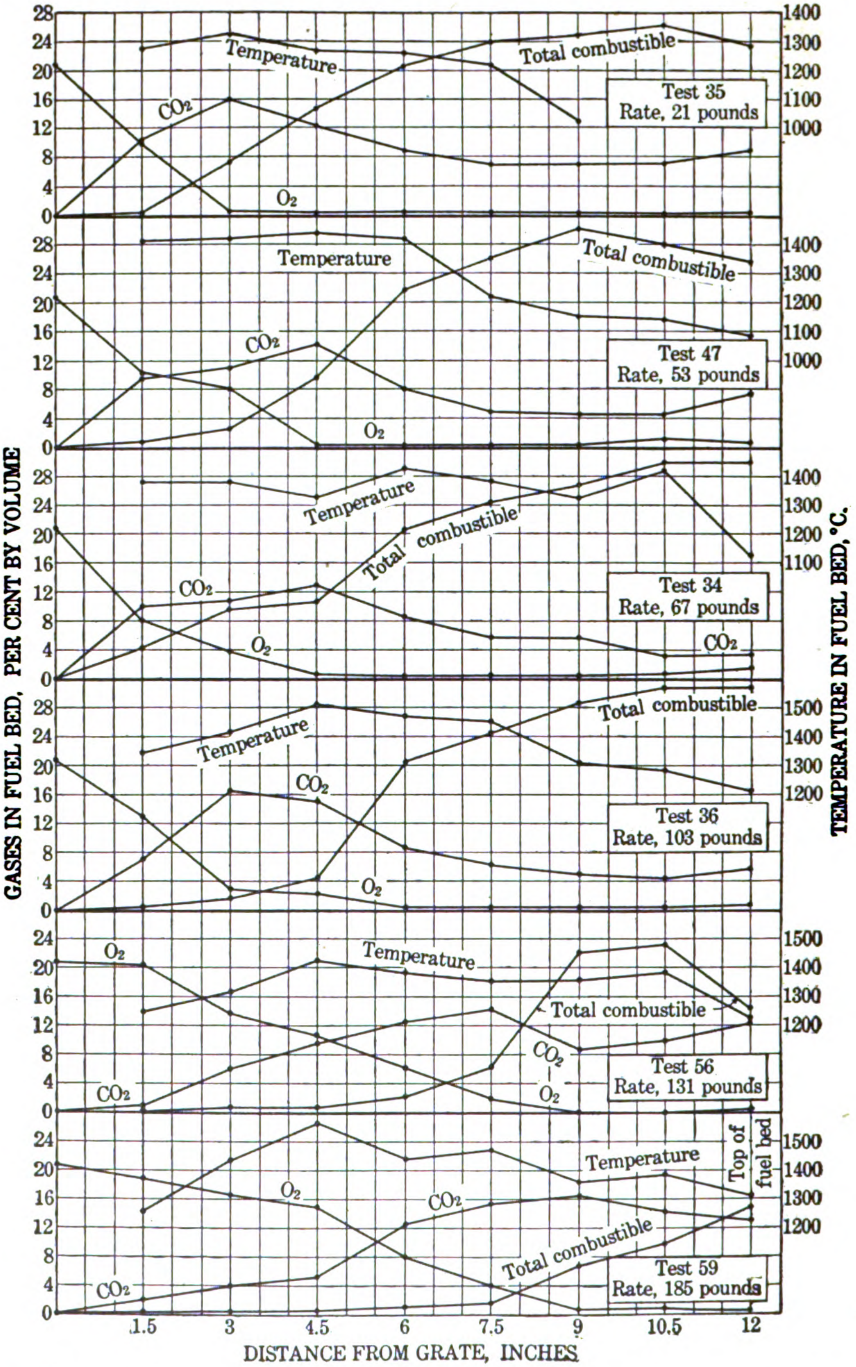


FIGURE 9.—Composition of gases and temperature in 12-inch fuel bed of Pittsburgh coal in a small hand-fired experimental furnace. Rates of combustion, 21, 53, 67, 103, 131, and 185 pounds of fuel per square foot of grate per hour.

Original from PRINCETON UNIVERSITY

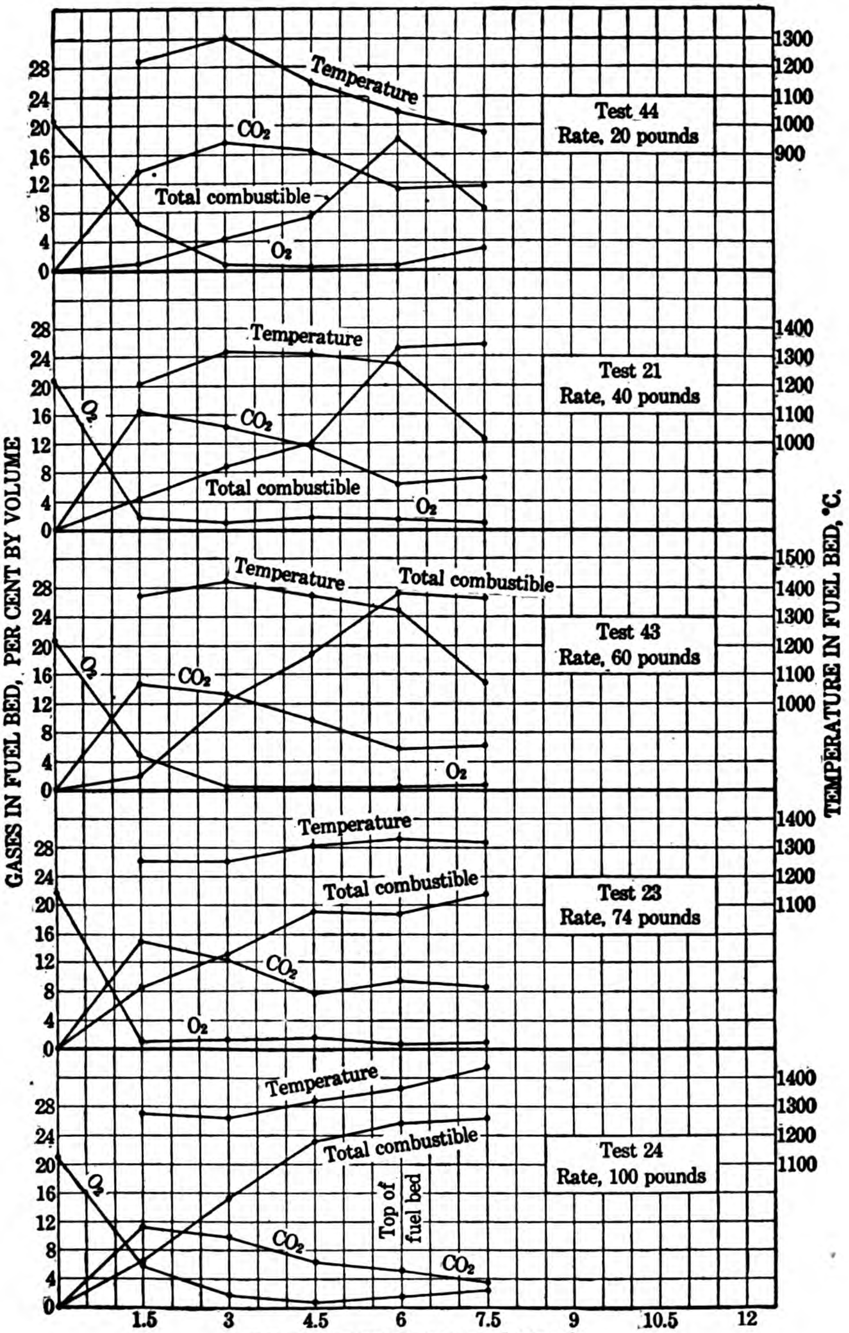


FIGURE 10.—Composition of gases and temperature in 6-inch fuel bed of anthracite coal in a small hand-fired experimental furnace. Rates of combustion, 20, 40, 60, 74, and 100 pounds of fuel per square foot of grate per hour.

Original from PRINCETON UNIVERSITY

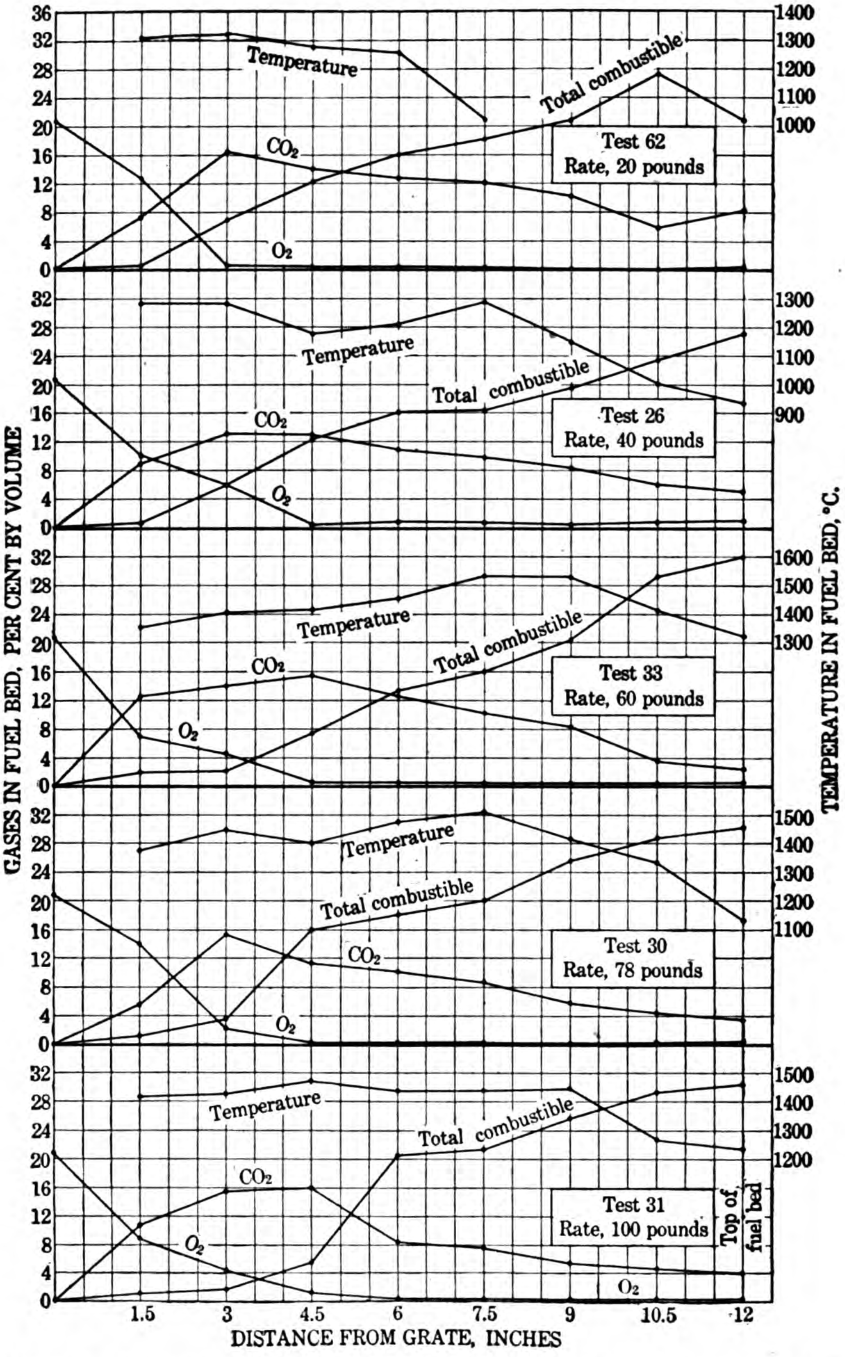


FIGURE 11.—Composition of gases and temperature in 12-inch fuel bed of anthracite coal in a small hand-fired experimental furnace. Rates of combustion, 20, 40, 60, 78, and 100 pounds of fuel per square foot of grate per hour.

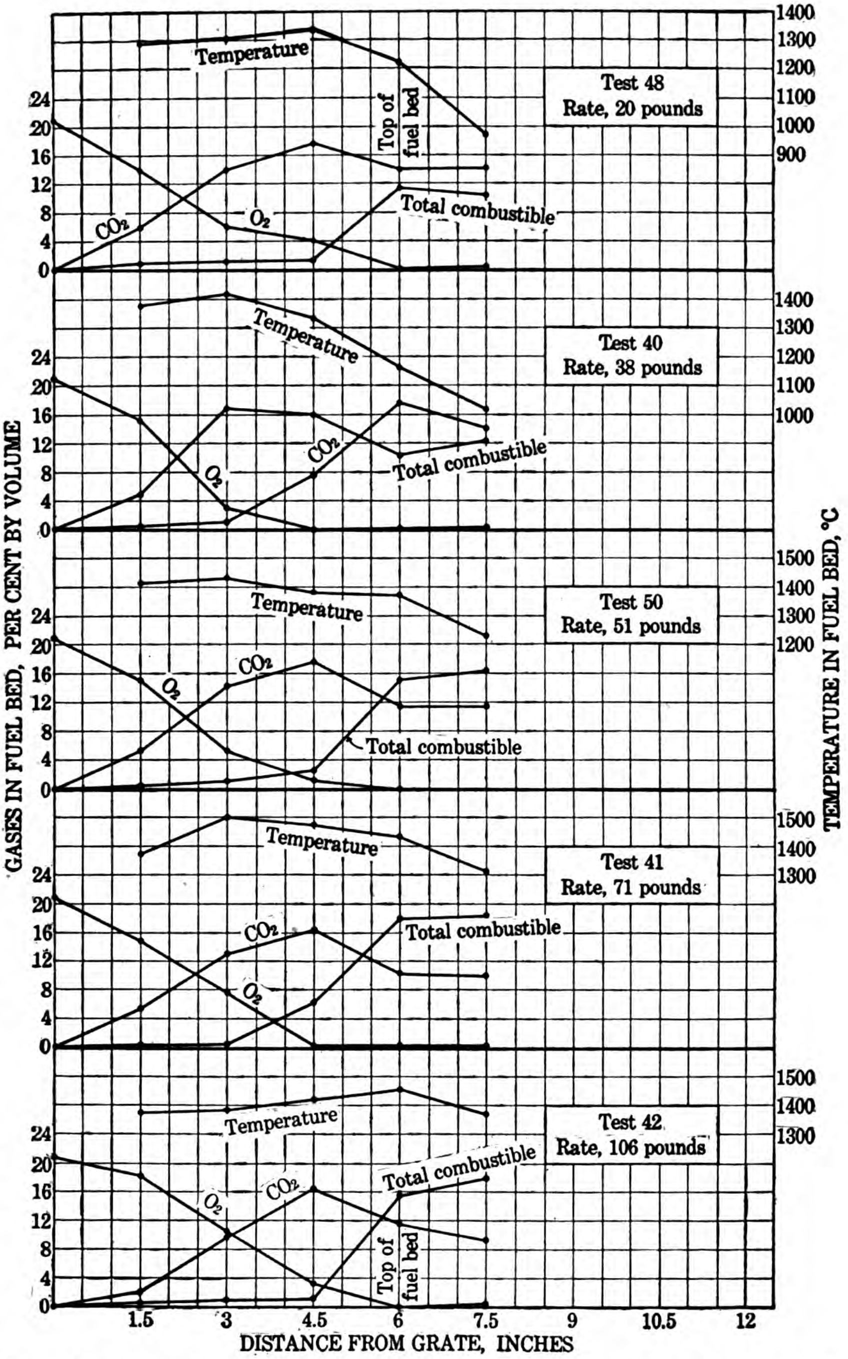


FIGURE 12.—Composition of gases and temperature in 6-inch fuel bed of coke in a small hand-fired experimental furnace. Rates of combustion, 20, 38, 51, 71, and 106 pounds of fuel per square foot of grate per hour.

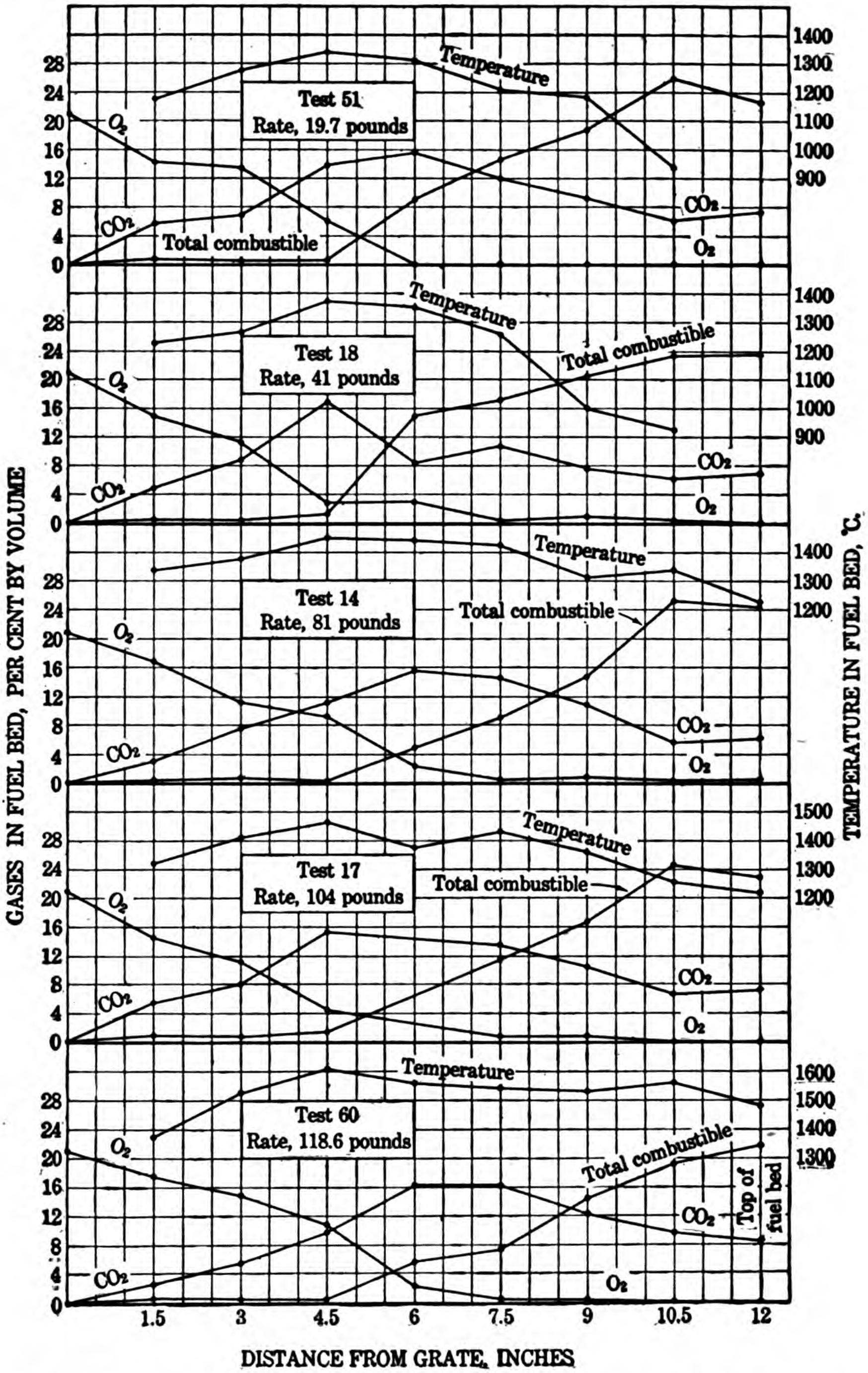


FIGURE 13.—Composition of gases and temperature in 12-inch fuel bed of coke in a small hand-fired experimental furnace. Rates of combustion, 19.7, 41, 81, 104, and 118.6 pounds per square foot of grate per hour.

Original from PRINCETON UNIVERSITY

At the surface of the fuel bed and 1½ inches above it the gases contained more oxygen, more CO_2, and less combustible than 1½ inches below the surface. This change in the composition of the gases was caused by air reaching the surface of the fuel bed from above, along the walls of the furnace, as shown in figure 14.

The effect of this downflow of air was much more marked with low rates of combustion than with high rates, because with the high rates the large volume of gases leaving the fuel bed more nearly filled the space above it and prevented the air from flowing down.

EFFECT OF ASH CONTENT AND ITS DISTRIBUTION.

The fact that with coke the oxygen does not disappear as quickly as with Pittsburgh and anthracite coal is probably caused by the higher percentage of ash in coke and its uniform distribution through the combustible. The ash in coal is not uniformly distributed, but is more or less concentrated in spots. On account of this partial concentration the ash in coal is probably more easily separated out of the fuel bed and shaken through the grate, so that the layers of fuel near the grate contain less ash and consequently use up more oxygen than when coke is used.

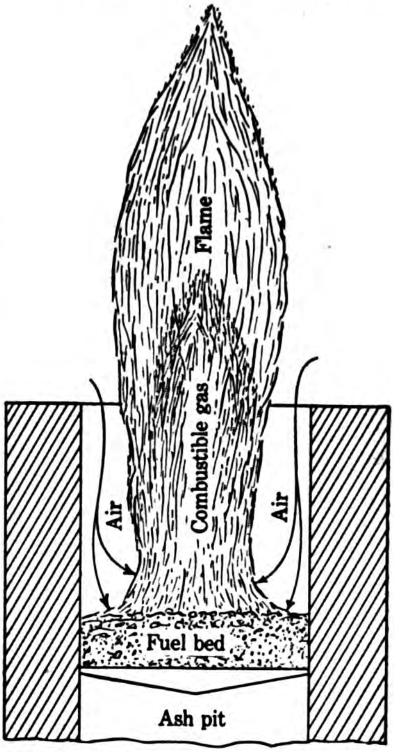


FIGURE 14.—Air flowing to the surface of fuel bed from top of furnace. The downward flow of air was distinctly noticeable with low rates of combustion.

THE THREE COMBUSTION PROCESSES.

It appears from figures 8 to 13 that the combustion in the fuel bed consists mainly of three processes, namely, the oxidation of carbon to CO_2, the reduction of CO_2 to CO, and the distillation of the volatile matter. Although with coke and anthracite coal the distillation process is unimportant, with bituminous coal it is of great significance. The combustion is the result of contact of two streams flowing in opposite directions. One of the streams is the air flowing up through the grate, the other is the fuel which is fed from the top and gradually sinks toward the grate. At the bottom of the fuel bed, where the air first comes in contact with the coal, the air contains 21 per cent of oxygen and the fuel bed but little combustible. On the other hand, at the top of the fuel bed there is practically no oxygen and a high percentage of combustible.

OXIDIZING ZONE AND RATE OF OXIDATION.

As the air passes up through the layer of fuel next to the grate the oxygen in it combines with the carbon of the coal. This reaction is expressed by the chemical equation $C+O_2=CO_2$. As the air passes through this layer the free oxygen rapidly diminishes and the CO_2 rises to its maximum content of 12 to 18 per cent, as shown in figures 8 to 13. The layer where CO_2 is formed is the oxidizing zone. In a 6-inch bed of bituminous coal this layer is 2 to 3 inches thick; in a 12-inch bed of coke it may be 4 or 5 inches thick.

The rate of oxidation in the lower part of the fuel bed depends almost entirely on the rate at which air flows through it. The greater the quantity of air that is forced through the fuel bed the faster the coal is oxidized or burned.

REDUCING ZONE AND RATE OF REDUCTION.

When the free oxygen is all used up, the CO_2 acts as an oxidizing agent, and by contact with the hot coal is reduced to CO. This reaction is expressed by the equation $CO_2+C=2CO$. The layer in the fuel bed where this process takes place is the reducing zone; it begins 2 to 3 inches above the grate and extends to the top of the fuel bed.

The rate of reduction of CO_2 to CO depends on the temperature of the fuel bed. The higher the temperature the faster the CO_2 is reduced to CO. The percentage of CO_2 that is reduced to CO at any given temperature depends, up to a certain limit, on the length of time that the CO_2 is in contact with the hot carbon. The longer the contact the larger is the percentage of CO_2 reduced to CO. The limit of reduction is the equilibrium between CO_2, CO, and carbon at the temperature existing in the fuel bed. Beyond this limit the percentage of CO_2 does not change, no matter how long the time of contact is.

At the high temperature existing in the fuel bed the reduction of CO_2 to CO is a rapid process, so that even during the short contact of CO_2 and hot carbon a considerable percentage of the CO_2 is reduced.

The rate of reduction of CO_2 to CO has been investigated by Clement, Adams, and Haskins.[a] Figure 15, which has been compiled from the results of their investigations, shows the effect of temperature and time of contact on the percentage of CO formed when CO_2 is in contact with hot coke.

---

[a] Clement, J. K., Adams, L. H., and Haskins, C. N., Essential factors in the formation of producer gas: Bull. 7, Bureau of Mines, 1911, 58 pp.

Digitized by Google Original from PRINCETON UNIVERSITY

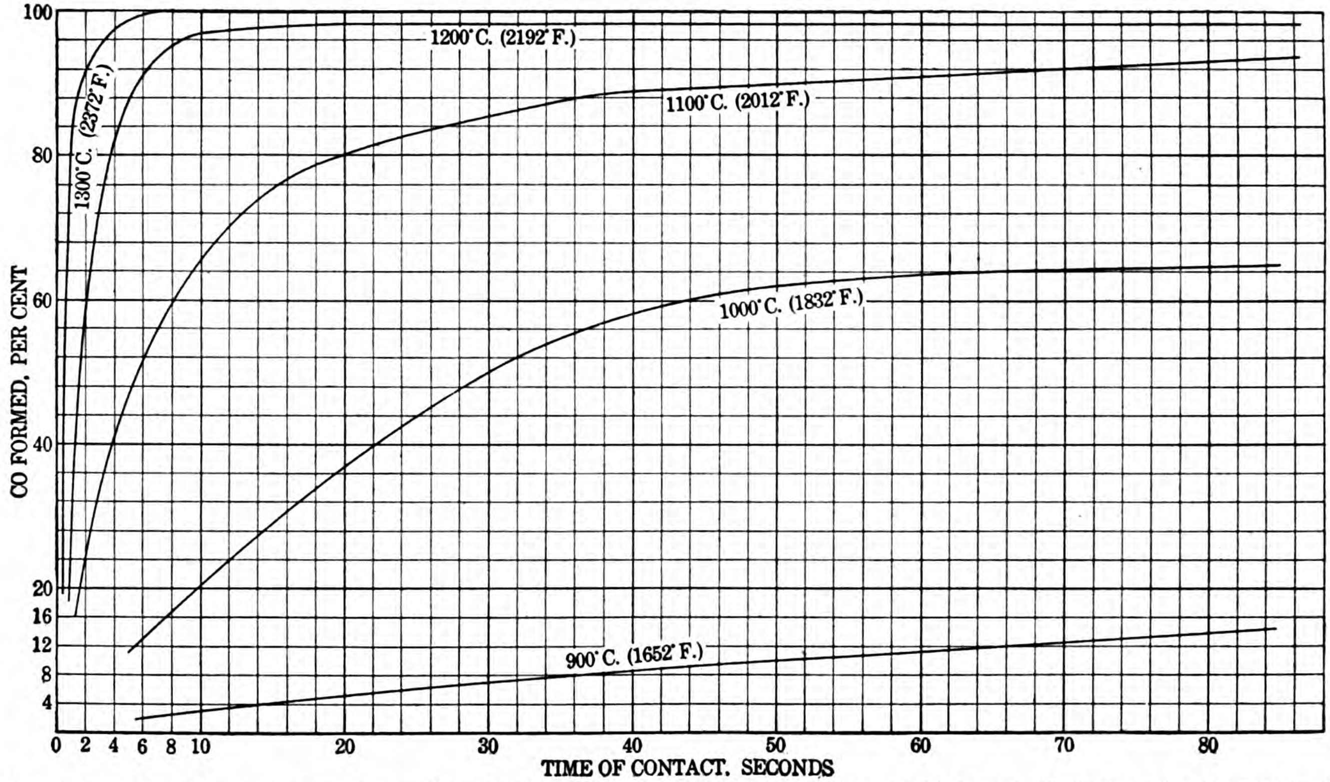


FIGURE 15.—Effect of temperature and time of contact of CO_2 with hot coke on the percentage of CO formed. Each curve gives the percentage of CO formed at one constant temperature.

The curves show that with low temperatures the percentage of CO formed is low, even though the time of contact is long; and that with high temperatures a large percentage of CO is formed in a very short time of contact. Thus, for example, with the temperature at 1,832° F., and after the gas had been in contact with the coke 50 seconds, the gas consisted of 62 per cent of CO and 38 per cent of CO_2. However, when the temperature of the coke was 2,372° F., the gas, after a contact of only 4 seconds, analyzed 98 per cent of CO and 2 per cent of CO_2. Inasmuch as the temperature of the fuel bed in a hand-fired furnace is about 2,400° F., the reduction of CO_2 is very rapid, so that a large percentage is reduced to CO although the time of contact is only a fraction of a second.

DISTILLATION ZONE AND RATE OF DISTILLATION.

The layer at the top of the fuel bed consists mostly of fresh fuel which is being heated and from which the volatile matter is being driven off. This layer is the distillation zone. It overlaps the reduction zone and extends about 2 inches below the surface of the fuel bed. The process of distillation is indicated by the occurrence of H_2, CH_4, unsaturated hydrocarbons, and tar and soot in the gases.

There is no sharp line of demarcation between the three zones, they pass gradually from one into the other. This is particularly true of the reduction and the distillation zones. The process of reduction continues almost to the surface of the fuel bed, and takes place with the distillation.

The rate of distillation depends on the rate of heating of the coal. The higher the temperature in the furnace, the higher the rate of heating of the freshly fired coal and the higher is the rate of distillation of volatile matter.

With a given temperature the distillation is independent of the air supply, as when coal is heated the volatile matter distills off whether air is supplied or not. In a gas retort all the volatile matter in the charge is distilled off in complete absence of air. On the other hand fixed carbon in a fuel bed can not be burned to CO_2 or gasified to CO without air being supplied through the grate. This is an important fact to be considered in combustion of coal in hand-fired furnaces. When the supply of air through the fuel bed is shut off by clinker or ash on the grate, the combustion of the fixed carbon stops. If, under such conditions, the coal is fed into the furnace with undiminished rate, only the volatile matter is distilled off and burns in the combustion space with the air supplied over the fuel bed, while the fixed carbon accumulates in the fuel bed, thus rapidly increasing its thickness.

COMBUSTIBLE LEAVING FUEL BED IN THE FORM OF SOOT AND TAR.

Not all the combustible leaves the fuel bed in the form of gas; some of it leaves in the form of soot, tar, and cinders. The weight

Original from PRINCETON UNIVERSITY

of soot and tar has been determined on eight tests with Pittsburgh coal and is given in columns 20 and 21 of Table 1 in grams per cubic foot of gas. To facilitate comparison of the weight of soot and tar with that of the gaseous combustible, the results of the analyses of the gases were reduced to grams per cubic foot of gas. These weights of the different combustible ingredients are given in Table 2.

Column 14 gives the combined weight of tar and soot in percentage of total combustible, including C in CO, CH_4, H_2, C_2H_4, tar and soot. As shown by this column, the tar and soot comprises, roughly, about one-fourth of the combustible rising from the fuel bed. This one-fourth of the combustible is in a form which is difficult to burn in the combustion space, and if no provision is made for its combustion a large part of it may go out of the chimney in the form of black smoke. It appears that smoke is formed near the surface of the fuel bed and goes out of the chimney because the air supply or the mixing or the size of the combustion space is inadequate for its combustion. It may be said, therefore, that in the extreme case about 25 per cent by weight of the combustible fired may go out of the chimney as black smoke.

It is possible that a large part of the volatile matter leaves the coal as tar, and that the tar immediately begins to break down into gaseous hydrocarbons and soot. Columns 10 and 11 of Table 2 show that near the surface of the fuel bed the weight of tar is about equal to the weight of soot. Extractions made on smoke collected from the chimney of a hand-fired horizontal tubular boiler showed only 3 to 6 per cent of tar. This small percentage of tar in the chimney smoke as compared to that found at the surface of the fuel bed indicates the decomposition of the tar into gases and soot as it passes through the furnace.

TEMPERATURE IN FUEL BED.

The temperatures in the different layers of the fuel bed are given by the top curves of figures 8 to 13, inclusive, along with the curves giving the composition of gases in the same layers. The temperatures as given in the charts are probably correct within 25° C. The glass plate which was placed over the observation holes when temperatures were being read was a microscope slide less than one thirty-second of an inch thick. By sighting the pyrometer on a frosted tungsten lamp no difference could be detected with the slide in and out. The slide was readily removable from the cap and was frequently cleaned during temperature observations. No corrections were therefore made for the plate. The estimated probable error of 25° C. is ascribed to the rapidly changing temperature in the little tunnel in the fuel bed.

TABLE 2.—*Data on combustible in gases from fuel bed.*

Test No.	Rate of combustion.	Thickness of fuel bed.	Distance of sample from grate.	Proportion in grams per cubic foot of total gases, at temperature of 60° F., and pressure of 30 inches of mercury.									Soot and tar, percentage of total combustible.
				C in CO.	CH_4.	H_2.	C_2H_4.	Total gaseous combustible.	Tar.	Soot.	Total soot and tar.	Total combustible.	
1	2	3	4	5	6	7	8	9	10	11	12	13	14
	Lbs.	*In.*	*In.*	*Grams.*	*Gram.*	*Gram.*	*Gram.*	*Grams.*	*Gram.*	*Gram.*	*Grams.*	*Grams.*	
52	22.3	6	4.5	2.459	0.218	0.109	0.145	2.931	0.549	0.227	0.776	3.707	20.9
			6	2.034	.628	.209	.732	3.603	.528	.482	1.010	4.613	21.9
			7.5	2.034	.317	.176	.211	2.738	.200	.450	.650	3.388	19.2
53	47.5	6	4.5	.707	.019	.007	.112	.845	.006	.048	.054	.899	6.0
			6	2.136	.142	.068	.036	2.382	.241	.369	.610	2.992	20.4
			7.5	2.506	.280	.175	.315	3.276	.335	.892	1.227	4.503	27.2
54	63.4	6	4.5	1.404	.018	.011	.180	1.613	.008	.036	.044	1.657	2.7
			6	1.466	.215	.072	.107	1.860	.107	.215	.322	2.182	14.7
			7.5	1.457	.304	.143	.286	2.190	.211	.669	.880	3.070	28.7
55	124	6	4.5	.158	.000	.004	.074	.236	.002	.000	.002	.238	.8
			6	1.488	.018	.014	.326	1.846	.004	.016	.020	1.866	1.1
			7.5	1.862	.142	.107	.356	2.467	.066	.227	.293	2.760	10.6
57	52	12	10.5	3.289	.206	.103	.103	3.701	.751	.553	1.304	5.005	26.0
			12	2.536	.484	.173	.242	3.435	.945	.477	1.422	4.857	29.3
			13.5	3.046	.311	.138	.207	3.702	.428	.374	.802	4.504	17.8
58	105.5	12	10.5	3.109	.069	.069	.035	3.182	.061	.137	.198	3.380	5.9
			12	2.522	.516	.241	.344	3.623	.658	.738	1.396	5.019	27.8
			13.5	2.475	.315	.140	.210	3.140	.311	.541	.852	3.992	21.3
56	131	12	10.5	3.149	.183	.183	.035	3.550	.148	.198	.346	3.896	8.9
			12	2.389	.036	.036	.036	2.497	.055	.092	.147	2.644	5.6
			13.5	2.888	.174	.104	.139	3.305	.147	.349	.496	3.801	13.0
59	185	12	10.5	1.205	.017	.037	.037	1.296	.017	.118	.135	1.431	9.4
			12	1.634	.108	.072	.036	1.850	.123	.415	.538	2.388	22.6
			13.5	2.248	.243	.209	.209	2.909	.369	.976	1.345	4.254	31.6

In general, the temperature is highest between the oxidizing and the reducing zone, approximately at the point of maximum CO_2 content in the gases. Farther away from the grate in the reducing zone the temperature gradually drops. This gradual drop is undoubtedly due to the reduction of CO_2, which is a heat absorbing process.

EFFECT OF RATE OF FEEDING AIR ON THE PROCESS OF COMBUSTION.

Within wide limits the rate of feeding air has practically no effect on the composition of gases within the fuel bed; that is, the composition of the gases at various depths in the fuel bed remains nearly the same no matter how much air is forced through the fuel bed. This is particularly true of the gases near the surface of the fuel bed. Comparison of the curves in figures 8 to 13 makes this fact apparent. All rates of combustion show that in the upper layers of the fuel bed there is 20 to 32 per cent of combustible gases with no free oxygen to burn it; that is, the free oxygen is all used up before the air reaches the top of the fuel bed no matter how fast the air is blown through.

RATE OF FEEDING AIR DETERMINES RATE OF COMBUSTION.

The rate of feeding air through the fuel bed affects directly the rate of combustion; that is, if the weight of air forced through the fuel bed in a given time is doubled, the rate of combustion of the fuel is doubled; if the weight of air is tripled, the rate of combustion is also tripled, and so on. In other words, the weight of air forced through the fuel bed per pound of fuel burned or gasified is constant, as is shown by the curves in figures 16 and 17.

In these curves the ratio of pounds of air used per pound of fuel is plotted with the rate of combustion. Two curves were plotted—the lower curve gives the pounds of air used per pound of fuel as fired, the upper curve the pounds of air used per pound of combustible. The two figures show that with any one fuel and any one thickness of fuel bed the points fall on a horizontal line of constant air supply; that is, the rate of combustion varies directly with the rate of feeding air through the grate. By increasing the rate of feeding air only the rate of combustion is increased and not the weight of air used per pound of combustible. It is therefore impossible to regulate the excess of air in any hand-fired furnace by increasing or decreasing the flow of air through a level fuel bed; only the rate of combustion can be controlled thereby.

FOR COMPLETE COMBUSTION AIR MUST BE ADDED OVER FUEL BED.

As the gases rising from the fuel bed contain a high percentage of combustible and no free oxygen, and as the air supply per pound of fuel can not be increased by increasing the rate of air supply through the fuel bed, it is apparent that to obtain complete combustion some air must be added over the fuel bed. Thus the percentage of CO_2 in the gases in any hand-fired furnace can be controlled only by regulating the supply of air admitted over the fuel bed. This fact and the one stated in last paragraph, namely, that by increasing the rate of feeding air through the fuel bed only the rate of combustion is increased, are important in the operation of hand-fired and some other types of furnaces.

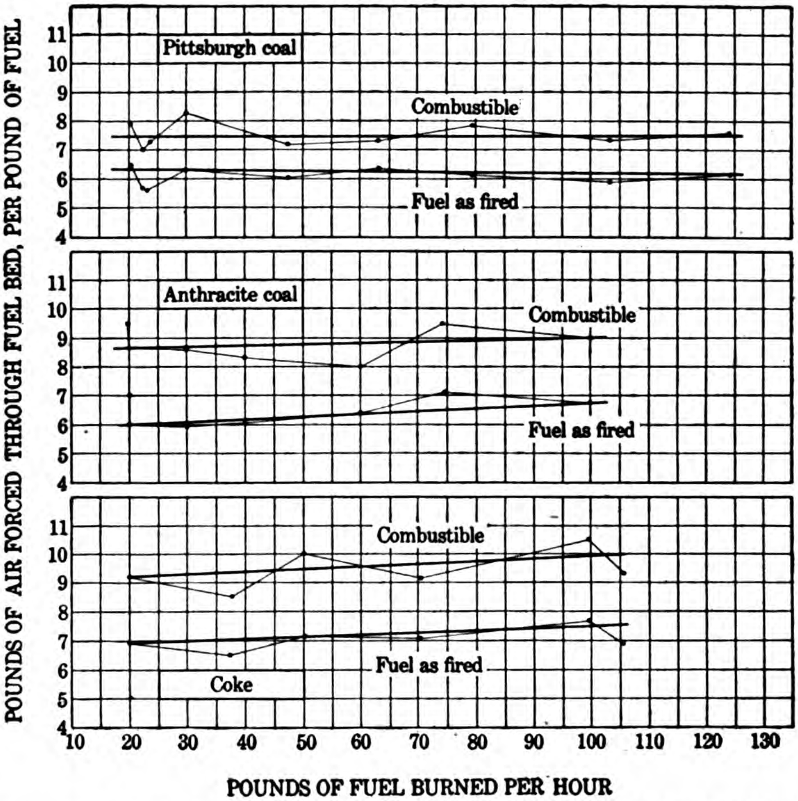


FIGURE 16.—Relation between the rate of combustion and pounds of air used per pound of fuel and combustible in 6-inch fuel bed. The upper curve of each pair gives the pounds of air per pound of combustible; the lower curve, pounds of air per pound of fuel as fired. The weight of air was obtained by measuring it with an orifice box.

It is well to state in this connection that forced-draft apparatus can not supply enough air through a level fuel bed to insure complete combustion. Additional air must always be introduced over the fire in such a manner that it will mix with the combustible gases, otherwise a large percentage of them escapes unburned.

Many a careful fireman has noticed that he makes less smoke and burns less coal if he keeps the dampers in the firing door open than when he keeps them shut tight. Frequently leaving the fire doors

Original from PRINCETON UNIVERSITY

partly open is found helpful in reducing the smoke to a great extent and results in saving coal. In some installations special openings are provided either in the front of the furnace or through the bridge wall for the introduction of air over or beyond the fuel bed. Partly open firing doors, or special openings in the furnace, supply additional air which burns the combustible gases rising from the fuel bed. The admission of air can be regulated to suit the rate of combustion and at the same time maintain efficient burning of coal.

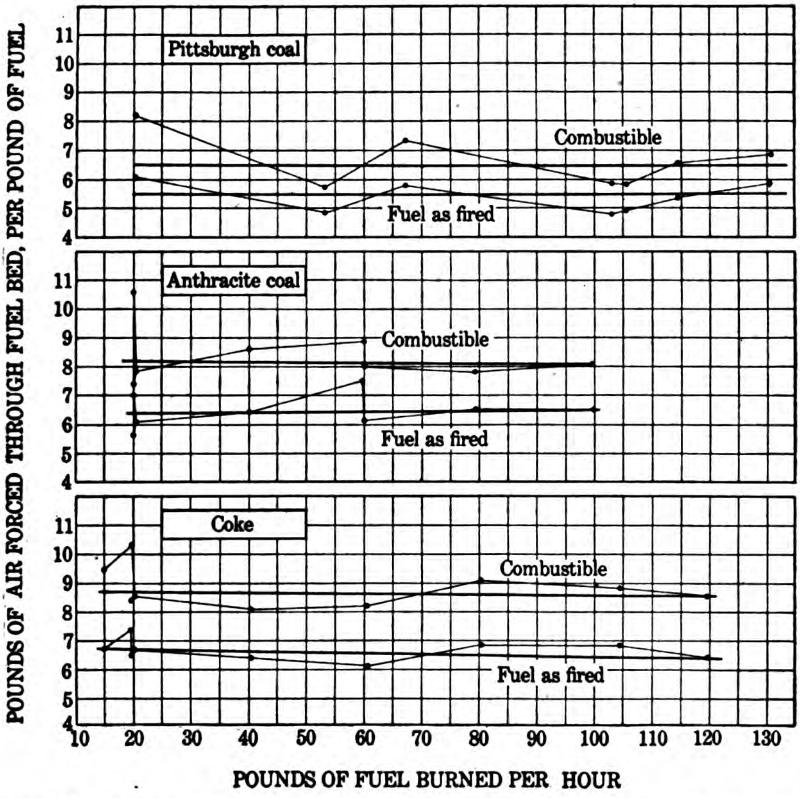


FIGURE 17.—Relation between the rate of combustion and pounds of air used per pound of fuel and combustible in a 12-inch fuel bed. The upper curve of each pair gives the pounds of air per pound of combustible; the lower curve, pounds of air per pound of fuel as fired. The weight of air was obtained by measuring it with an orifice box.

ADDITIONAL AIR ADMITTED THROUGH HOLES IN FIRES AND LEAKS IN FURNACE.

With a level fuel bed and an absolutely tight furnace perfect combustion would be impossible even when burning anthracite coal or coke. However, such conditions are seldom or never found in practice. The firing may be done so poorly that there are thin spots or holes in the fuel bed a large part of the time. Through these holes

Original from PRINCETON UNIVERSITY

air may enter the furnace in sufficient volume not only to make complete combustion possible, but often to raise the supply of air far beyond the most economical quantity, and cause excessive chimney losses.

The fire doors never fit tight, neither are the brick furnace walls free from leaks, so that in some cases the leakage around the furnace doors and through the brickwork is far more than enough for complete combustion. Thus careless firing and a neglected boiler furnace and setting may cause the addition of air over the fuel bed to appear unnecessary.

ADMISSION OF AIR THROUGH HOLES IN FIRES AND LEAKS IN FURNACE UNDESIRABLE.

From what has been said in the last paragraph it might seem that careless firing resulting in holes in the fire, or a leaky furnace and setting, were desirable features as they introduce additional air over the fuel bed and thus to some extent aid complete combustion. However, holes in the fire and leaks in the furnace are most undesirable methods of introducing air into furnaces and deserve condemnation, as the amount of air introduced into the furnace can not be regulated to suit the requirements.

The holes in the fire are small immediately after the firing and grow larger as the coal burns out. Thus when large volumes of volatile combustible are rising from the fuel bed immediately after firing and when a large amount of air is needed the quantity of air admitted is small. As the coal burns out and the holes become larger, more air is admitted into the furnace. At the same time the volume of combustible gases rising from the fuel bed becomes smaller; first, because the greater part of the volatile matter has already been driven off, and, second, because holes in the fire reduce the pressure drop from the ash pit to the furnace, thereby decreasing the flow of air through the covered part of the grate, with the result that less fuel is gasified than with no holes in the fire. Therefore, less air is needed to burn this smaller volume of combustible gases, so that the quantity of air flowing into the furnace through the holes in the fire is far in excess of the amount actually needed for complete combustion. Thus when air is introduced through holes in the fuel bed there is incomplete combustion owing to insufficient air at one time and entirely too large an excess of air shortly afterwards.

The leakage of air into the furnace increases as the draft becomes higher, and the draft in the furnace increases as the clinker accumulates on the grate, or as the fuel bed through any cause becomes thicker. Clinker on the grate and thick fires also reduce the flow of air through the fuel bed, thereby reducing the rate of combustion or gasification of the fuel on the grate. Thus with clinker on the grate or thick fires there is a large amount of air leaking into the furnace when a small volume of combustible gases is being generated, and not enough air when the fuel bed is clean and thin and a large volume of combustible gas is being generated. For these reasons admission of air into the furnace through leaks in the furnace walls is undesirable and should be avoided.

The ideal way to supply additional air over the fuel bed is to introduce it as close to the fuel bed and in as large a number of small streams as possible. The nearer the air is introduced to the surface of the fuel bed, the more combustion space is utilized for mixing air with the combustible gases and for burning the mixture. A large number of small streams of air entering the furnace facilitates mixing the air with the combustible gases, particularly if it is forced in at high velocity. When the air is introduced in one large stream at low velocity it tends to flow parallel to the stream of combustible gases without mixing with them, thus causing slow combustion. The rate of mixing determines the rapidity of combustion of the combustible gases. With a perfect mixture and the usual furnace temperature the velocity of combustion is very great indeed, so that the combustion is almost of the nature of an explosion.

RELATION BETWEEN PRESSURE DROP THROUGH FUEL BED AND RATE OF COMBUSTION.

The relation between the pressure drop through the fuel bed and the rate at which air flows through the beds of the three fuels is shown by the curves in figure 18. The ordinate is the pressure in the ash pit which is nearly the same as the pressure drop through the fuel bed, the pressure above the fuel bed being nearly atmospheric. The abscissa is the weight of air in pounds flowing through the fuel bed per hour as measured by the orifice. This flow of air is directly proportional to the rate of combustion.

The two thicknesses of fuel beds used, 6 inches and 12 inches, make two separate groups of points, each lying on a curve having a parabolic shape, and represented by the following equation:

$$W^n = CP$$

W = weight of air passing through fuel bed.
C = a constant.
P = pressure drop through fuel bed.

However, the index of the power ^{n} is not equal to 2 but only to about 1.7. In figure 18 the smooth curves are the graphs of the above equation where ^{n} equals 1.7. The points representing the tests fall reasonably close to these smooth curves.

The fact that the points lie on both sides of the smooth curve can be accounted for by the varying condition of the fuel bed owing to accumulation of clinker and ash. The presence of clinker and ash in the fuel bed greatly affects its resistance to flow of air, thereby also affecting the pressure drop through the fuel bed. This variation in the clinker and ash content of the fuel bed was difficult to eliminate.

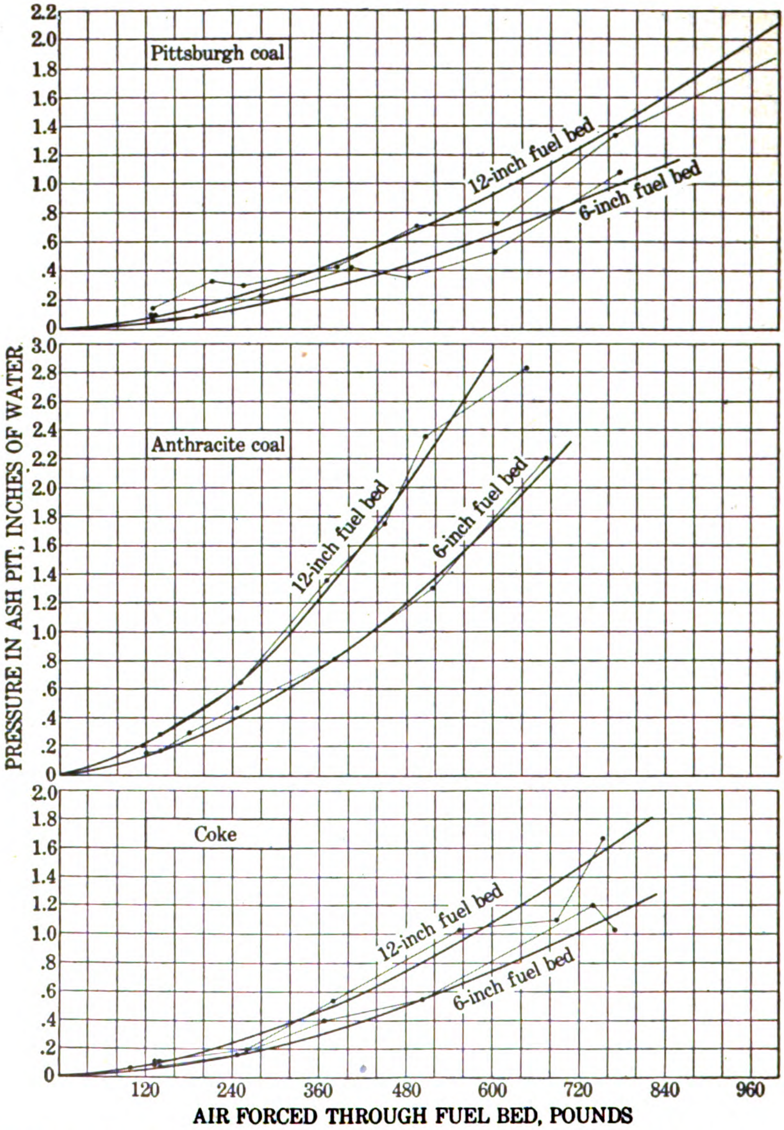


FIGURE 18.—Relation between the pressure in the ash pit (apparent pressure drop through fuel bed) and the weight of air flowing through fuel bed. The weight of air was determined with an orifice box.

It is usually stated that the pressure drop through the fuel bed varies as the square of the weight of air passing through it; or, that the weight of air passing through the fuel bed varies as the square root of the pressure drop. According to figure 18 such rules are only approximate, but can be used safely in figuring the rate of combustion from pressure drops; that is, the actual rate of combustion is somewhat higher than the values computed on the basis of squares or square roots.

EFFECT OF NATURE OF COAL ON PRESSURE DROP THROUGH FUEL BED.

Comparison of the pressure drops through the fuel bed for the three fuels shows that with the anthracite coal used the pressure drop is higher than with either the Pittsburgh coal or the coke. This means that the resistance to the flow of air through anthracite is higher. The cause of this higher resistance is difficult to explain. It is probably due to the fact that the anthracite coal cracked or popped when heated. Small pieces one-quarter to one-half inch across, cracked off and filled the voids between the larger pieces, thus increasing the resistance to the flow of air through the fuel bed.

The pressure drops with the Pittsburgh coal and with the coke show no appreciable difference. Evidently the two fuels act similarly when heated, as far as change in shape and physical structure are concerned.

That the nature of coal may have a very marked effect on the resistance of the fuel bed to the flow of air through it is indicated by Plate II. The plate shows four pieces of Pittsburgh coal (*P1* to *P4*) and four of Alaska Bering River coal (*A1* to *A4*) after they had been heated in a furnace at 1500° F. until the volatile matter was driven off. Both pieces *P1* and *A1* were originally one-inch cubes like the one shown between the two pieces and marked *1*. The pieces *P2*, *P3*, *A2*, and *A3* were originally three-fourths inch cubes like the one shown in the center of the plate and marked *2*. Figures *P4* and *A4* show slack coal subjected to the same treatment as the cubes. The plate shows that the behavior of the two coals is vastly different. The Pittsburgh coal when heated practically retains its original size and shape, whereas the Alaska coal runs into fingers and expands in volume. This fingering and swelling of the Alaska coal may change very much the resistance of the fuel bed. It would seem that with the Alaska coal the fingering would increase the voids in the fuel bed, thus considerably decreasing its resistance to the flow of air through it, provided the fuel bed is not disturbed with fire tools, in which case the fingers would be broken off and tend to fill the voids.

The preceding considerations go to show that the resistance of the fuel bed to the flow of air through it depends not only on the size of the fuel but to an even larger extent on the nature of the coal. This is an important fact which must be taken into consideration in estimating the rate of combustion for different coals for a given available draft.

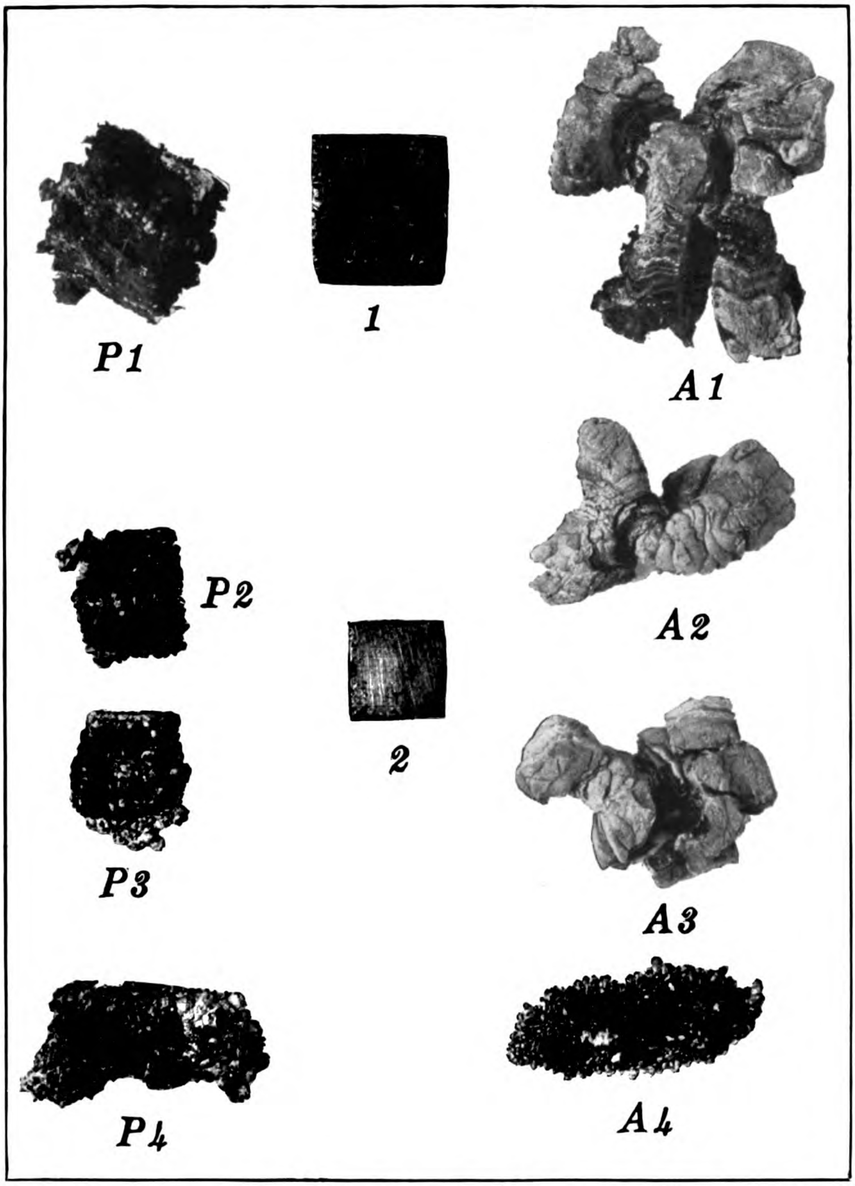
AIR USED PER POUND OF COMBUSTIBLE.

The weight of air per pound of combustible, computed from the analysis of the gases, varies according to the place where the gas sample was taken. With samples taken near the grate the computed weight is high and decreases with the gas samples taken farther away from the grate. Near the surface of the fuel bed the weight of air is the lowest. In order to show this gradual decrease the weight of air has been computed in several tests for all the gas samples taken. Thus in test 50, made with coke and a 6-inch fuel bed, the weight of air 1½ inches from the grate is 41.1 pounds per pound of combustible burned up to that point. Beyond that point it decreases, at first rapidly and then slowly, to 8.2 pounds at the surface of the fuel bed. A similar variable decrease is shown in tests 16, 43, and 33, for which calculations were made.

The reason for this decrease in the computed weight of air is that as the air passes up through the fuel bed it continually picks up carbon and other combustible, and thus the ratio of air to combustible becomes smaller. When the air enters the fuel bed all of its oxygen is free—that is, it is not combined with any carbon or other combustible; therefore at that point the ratio of air to combustible burned is infinitely large. As the air passes through the lower layers of the fuel bed the free oxygen combines with carbon to form CO_2 until most of the oxygen is used up. Then as the CO_2 passes through the upper layers of the fuel bed the CO_2 combines with some more carbon and is reduced to CO. Thus the amount of carbon that has combined with the air gradually increases, causing the ratio of air to combustible to become smaller.

In most of the tests the weight of air was computed only for the samples of gas taken at the surface of the fuel bed and 1½ inches below the surface. Above the surface of the fuel bed no carbon is gasified so that the gas sample taken at the surface gives the composition of gases at the end of the process of combustion in the fuel bed. The weight of air per pound of combustible computed from the analysis of gases taken at the surface of the fuel bed should be approximately the same as that obtained by measuring the air with an orifice. A comparison of these computed values with those given in column 10 of Table 1 shows that the weight of air measured with the orifice is in general somewhat higher. This may be due to several causes, the main ones being as follows:

The measurement of air with the orifice may be 2 to 5 per cent in error, which may make the weight too large.



COAL THAT HAS BEEN HEATED AT 1,500° F. UNTIL VOLATILE MATTER HAS BEEN DRIVEN OFF. *P1* TO *P4*, PITTSBURGH COAL; *A1* TO *A4*, ALASKA BERING RIVER COAL; *1*, SIZE OF PIECES *P1* AND *A1* BEFORE HEATING; *2*, SIZE OF PIECES *P2*, *P3*, *A2*, AND *A3* BEFORE HEATING. *P4* AND *A4* WERE SLACK SAMPLES.

Some of the air after being measured with the orifice may have leaked out of the ash pit around the cleaning door and the shaking bars of the grate and through various small leaks in the apparatus, although in the tests every precaution was taken to prevent such leaks.

When a test was started the fuel bed contained mostly combustible and very little clinker and ashes; when a test was closed the fuel bed contained a large quantity of clinker and less combustible. Therefore more combustible was really burned than the amount computed from the weight of coal fired and its analysis.

More air may have been passing up along the wall of the furnace than near the center of the grate, where the samples of gases were collected.

EFFECT OF THICKNESS OF FUEL BFD ON PRESSURE DROP.

With the same kind of fuel and the same rate of combustion an increase in thickness of fuel bed is accompanied with approximately a proportional increase in the pressure drop through the fuel bed. That is, when the thickness of fuel bed is doubled the pressure drop through it is about doubled. This rule was found to hold true for the isothermal flow of air through beds of shot in experiments presented in Bulletin 21.[a] Figure 18 shows that this rule holds also fairly well for the flow of air through beds of burning fuel. The 12-inch fuel bed takes about twice as much pressure drop as the 6-inch fuel bed. Part of the deviation from this rule can be accounted for by the fact that the pressure drop is not altogether used to push the gases through the fuel bed, but also to impart to the gases the velocity with which they leave the fuel bed. That is, part of the static pressure under the fuel bed is converted into dynamic pressure above the fuel bed. As with the same rate of combustion the gases leave the fuel bed at about the same velocity, the dynamic pressure of the gases at the top of the fuel bed is the same with both thicknesses of fuel bed. Therefore to get the true pressure drop through a fuel bed the dynamic pressure, which is the same for the gases at the top of each fuel bed, should be subtracted from the total pressure drop given in column 5 of Table 1. This feature is shown in figure 19, which shows that although the true pressure drop through the 12-inch fuel bed may be exactly twice the drop through the 6-inch bed, the total pressure drops do not have the same ratio because each is too large by a magnitude equal to the dynamic head, which is the same for each.

That the dynamic head is of appreciable magnitude, especially at high rates of combustion, is indicated by the fact that small pieces of coal are lifted by the gases from the fuel bed and often carried out through the stack.

---

[a] Ray, W. T., and Kreisinger, Henry, The significance of drafts in steam-boiler practice: Bull. 21, Bureau of Mines, 64 pp.

The dynamic head should always be considered in all measurements of pressure (drafts) in boiler settings. Usually only the static part of the pressure is considered, the dynamic part being left out altogether. On account of this omission, results may sometimes show that the gases flow from a point of lower pressure to a point of higher pressure.

Inasmuch as a higher pressure drop is necessary to push the same quantity of air through a thick fuel than through a thin one, with thick fuel beds higher stacks are necessary, or. in locomotives, higher back pressure in the steam cylinders.

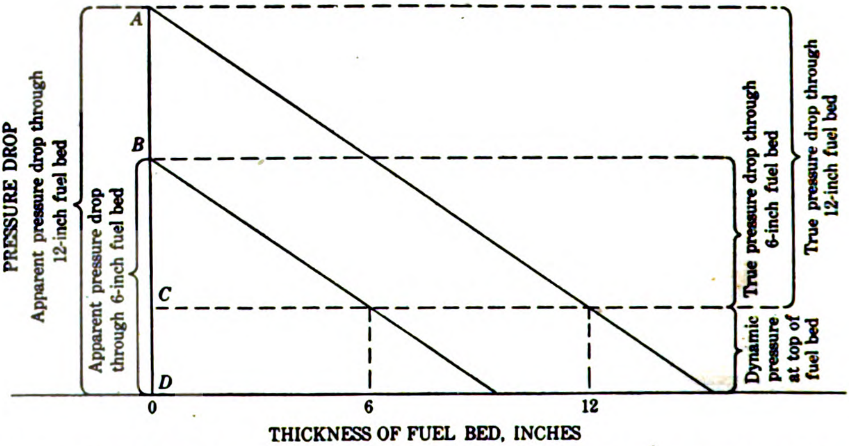

PRESSURE DROP
Apparent pressure drop through 12-inch fuel bed
Apparent pressure drop through 6-inch fuel bed
A
B
C
D
True pressure drop through 6-inch fuel bed
True pressure drop through 12-inch fuel bed
Dynamic pressure at top of fuel bed
0
6
12
THICKNESS OF FUEL BED, INCHES

FIGURE 19.—Diagram showing the relation between the apparent pressure drop and the true pressure drop through the fuel bed. The apparent pressure drop AD through a 12-inch fuel bed is equal to the true pressure drop AC plus the dynamic pressure CD at the top of the fuel bed. The apparent pressure drop BD through a 6-inch fuel bed is equal to the true pressure drop BC plus the same dynamic pressure CD at the top of the fuel bed.

FUSION OF ASH IN FUEL BED.

In all instances when clinker was formed, the fusion of the ash occurred 3 to 4 inches above the grate with 6-inch fuel beds and even as high as 10 inches with 12-inch fuel beds. Each time the grate was shaken the ash could be seen to pass the hole that was 3 inches above the grate in a half-fused viscous state, showing that the fusing or softening of the refuse took place in the upper layers of the fuel bed. When a test was closed and the fuel bed was dumped, a ring of clinker was found on the wall extending from a point 2 or 3 inches above the grate to 4 or 5 inches above it with a 6-inch bed, and to as high as 10 inches with a 12-inch bed. The formation of the clinker on the wall of the furnace is shown in figure 20.

The ring of clinker and the observations of the ash, made through the hole 3 inches above the grate, indicate that any fusion which takes place occurs largely in the reducing zone of the fuel bed. As the half molten, sticky ash sinks toward the grate, it passes into the oxidizing zone and solidifies, although this layer of fuel bed, where the clinker solidifies, usually has the highest temperature.

It should be remembered that the reducing zone contains not only combustible (reducing) gases, but also a considerable percentage of CO_2, which is not a reducing gas. The zone is called reducing because in it the CO_2 is being reduced to CO; a distinction must be made between reducing zone and reducing atmosphere.

Fieldner, Hall, and Feild[a] found that the fusion temperature of coal ash is much lower in a partly reducing than in a strongly oxidizing or strongly reducing atmosphere. A study of the gas composition charts (figs. 8 to 13) shows that the melting occurs in the layer where the gases contain about 10 per cent of combustible gases, 10 to 12 per cent of CO_2, and very little or no oxygen.

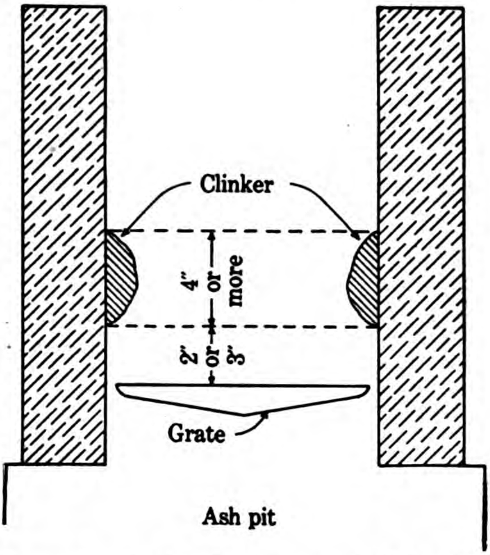


FIGURE 20.—Section showing zone of clinker formation in small experimental furnace.

DATA ON COMBUSTION IN FUEL BEDS OF OTHER FURNACES.

COMPOSITION OF GASES RISING FROM FUEL BED OF A HAND-FIRED HEINE BOILER.

In the steaming tests of coals reported in Bulletin 23,[b] the composition of six consecutive samples of the gases rising from the fuel bed of a hand-fired Heine boiler during three minutes immediately after firing was ascertained. The samples were collected with a water-cooled gas sampler laid in a horizontal position on the surface of the fuel bed. The length of time during which each sample was collected was 30 seconds, each sample being collected in a separate bottle. The thickness of the fuel bed did not exceed 4 inches. The coal used was Collinsville, Ill., nut size. The samples were collected and analyzed by Perry Barker, chemist of the steam engineering section. The results of the analysis were as follows:

---

[a] Fieldner, A. C., and Hall, A. E., The fusibility of coal ash in various atmospheres: Jour. Ind. Eng. Chem., vol. 7, 1915, p. 399; Fieldner, A. C., and Feild, A. L., The fusibility of coal ash in mixtures of hydrogen and water vapor: Jour. Ind. Eng. Chem., vol. 7, 1915, p. 742.

[b] Breckenridge, L. P., Kreisinger, Henry, and Ray, W. T., Steaming tests of coals and related investigations, Sept. 1, 1904, to Dec. 31, 1908: Bull. 23, Bureau of Mines, 1912, p. 282.

Analysis of gases leaving fuel bed for three minutes after a firing.[a]

[Test made in a Heine hand-fired boiler, Feb. 4, 1907, on nut coal from Collinsville, Ill.]

Time during which sample was taken.	Percentage by volume.						
	CO_2.	O_2.	CO.	C_nH_{2n}.	H_2.	CH_4.	Total combustible.
First half minute	7.6	2.3	18.3	0.2	1.0	1.2	20.7
Second half minute	6.9	1.0	19.8	.3	3.6	1.4	25.1
Third half minute	4.7	.7	20.1	.4	5.5 5.8	2.6 2.5	28.6 28.8
Fourth half minute	4.8	2.2	17.4	.4	4.2 5.0	4.5 4.3	26.5 27.1
Fifth half minute	5.9	1.4	19.1	.2	7.6	3.0	29.9
Sixth half minute	6.6	1.6	15.8	.0	6.8	4.1	26.7

[a] Bureau of Mines Bull., 23 p. 282.

The gases in the column with heading C_nH_{2n} are unsaturated hydrocarbons; they were determined by absorption in fuming sulphuric acid. Hydrogen and methane were obtained by the explosion method; CO_2, O_2, and CO were determined by absorption in the solutions as used in an Orsat apparatus for the same purpose. The tar vapors, upon entering the water-jacketed gas sampler, were condensed to liquid or solid and could not be determined by a volumetric method.

The results of the analyses agree well with those made on samples taken at the surface of the fuel bed in the tests with the small experimental furnace reported in this paper. The high percentage of total combustible in the gases rising from the fuel bed makes the product a fairly good producer gas, showing that the fuel bed acts primarily as a gas producer.

COMBUSTION PROCESS IN FUEL BED OF A MURPHY STOKER.

The fuel bed acts as a gas producer not only in a hand-fired furnace but also in other types of furnaces. Thus, the gases rising from the fuel bed of a Murphy stoker contain a high percentage of combustible and very little free oxygen. Six gas samples were collected simultaneously near the surface of a 6-inch fuel bed of a Murphy stoker burning Pittsburgh coal with water-cooled samplers during a period

Digitized by Google Original from PRINCETON UNIVERSITY

of about 30 minutes. The rate of combustion was 47 pounds of coal per square foot of grate per hour. The grate area was 25 square feet and the six samplers were uniformly distributed over the grate. The average analysis of the six samples was as follows:

Composition of gases at the surface of a 6-inch fuel bed of a Murphy Stoker.

	Per cent.
CO_2	6.2
O_2	3.4
CO	13.4
CH_4	1.0
H_2	9.0
Total combustible	23.4

Air was forced into the furnace through the tuyères immediately over the fuel bed, so that some of this air possibly found its way into the samplers along with the combustible gas. The mixture was quickly cooled in the samplers before much of the combustible gas was burned. The percentage of CO_2 and free oxygen is low and that of the combustible high. With the free oxygen present only a small part of the combustible gas could be completely burned.

The composition of the gases, as given above, shows that the fuel bed in a Murphy stoker acts primarily as a gas producer, and that if the fuel bed is kept level air must be introduced over the fire in order to obtain complete combustion.

COMBUSTION PROCESS IN FUEL BED OF A JONES UNDERFEED STOKER.

The fuel bed of a Jones underfeed stoker also acts as a gas producer, the combustible leaving the fuel bed not as products of complete combustion but mostly as combustible gas; that is, in the fuel bed the fuel is not completely burned but is only gasified. This fact is shown by the analyses of six samples of gases collected at different distances from the top of the fuel bed in a furnace equipped with a Jones underfeed stoker. The samples were collected at different times with the fuel bed in approximately the same condition. The samples were taken with an exhausted gas container which was water-cooled and were grab samples. They were collected and analyzed by J. C. W. Frazer, chemist of the fuel-testing division. The results of the analyses were as follows.

Analysis of gases leaving fuel bed of a Jones underfeed stoker, New River coal.

Date.	Time of collection.	Temperature.	Distance into furnace.	Per cent of normal capacity.	Hydrocarbon vapors.	CO_2.	Unsaturated hydrocarbons.	O_2.	CO.	CH_4.	H_2.	N_2.	Total combustible.
1	2	3	4	5	6	7	8	9	10	11	12	13	14
1907.	*p. m.*	°*C.*	*In.*			*P. ct.*	*P. ct.*	*P. ct*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*	*P. ct.*
Oct. 21	4.40	1,455	21	100	(*a*)	8.9	0.1	0.2	15.9	0.2	3.0	71.7	16.2
21	4.00	1,450	20	100	(*a*)	5.4	.2	.3	22.3	.54	3.0	68.4	25.94
15	2.00	1,350	16	75	(*a*)	5.0	.2	.4	21.9	1.0	3.0	68.5	26.1
23	3.00	1,460	12	125	(*a*)	13.3	.1	1.1	9.3	.0	1.0	75.2	10.4
15	1.30	1,420	10	75	(*a*)	16.2	.0	2.3	2.1	.0	.0	79.4	2.1
23	2.20	1,460	6	130	(*a*)	9.9	.2	10.5	.1	......	......	79.3	.3

a Not determined.

The location in the furnace where the samples were taken is shown in figure 21, and the distance of the intake of the sampler from the inside of the furnace wall is given in column 4 of the table.

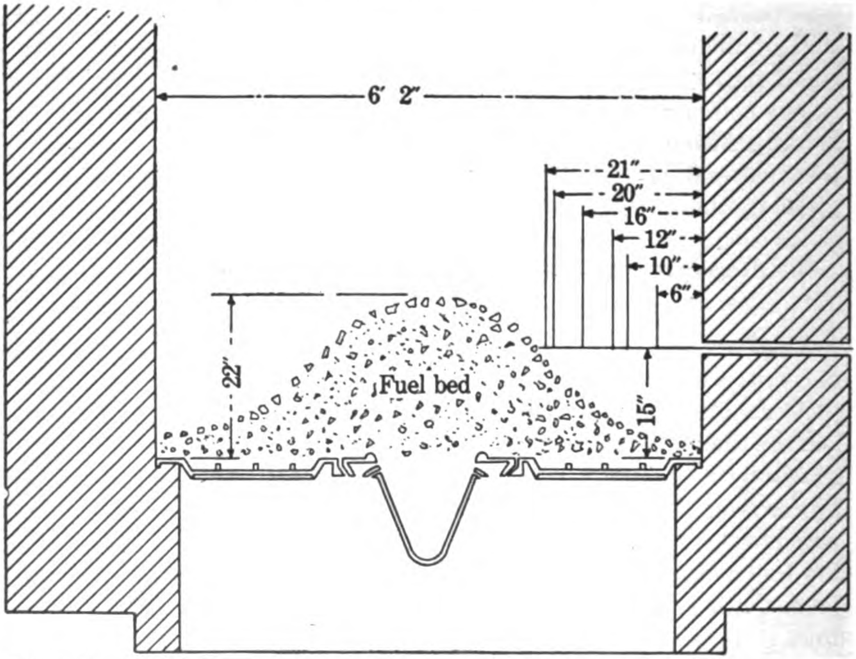


FIGURE 21.—Section showing where gas samples were taken above fuel bed of Jones underfeed stoker.

The analyses show that the gases were richest in combustible and contained practically no free oxygen when the sampling apparatus protruded from 16 to 21 inches into the furnace, that is, when the intake was near the burning heap of coal. The oxygen supplied through the tuyères was all used up in burning the carbon to CO_2, which was then reduced to CO.

BEARING OF RESULTS OF TESTS ON OPERATION OF GAS PRODUCERS.

The rapid combustion and gasification of coal shown by the results of the tests presented in this report suggest the possibility of operating gas producers at a very high rate. It seems that it is possible to obtain rich gas with a rate of gasification of 100 to 200 pounds of coal per hour for each square foot of cross section of the gas generator. Thick fuel beds do not seem to be necessary for rich gas; perhaps a thickness of 2 to 3 feet is all that is needed to keep the percentage of CO_2 in the gas low. The one condition that is necessary for a high rate of gasification and rich gas is high temperature.

With temperatures above 1,300° C. the reduction of CO_2 to CO is very rapid. This fact was pointed out in Bulletin 7,[a] in which it was suggested that a gas producer be operated at high temperature, thus making it possible to gasify coal at rates several times that ordinarily used. High rates of gasification would tend to reduce the first cost of the producer plant, and high temperature would appreciably reduce the percentage of tar in the gases.

One difficulty that would be encountered in operating a gas producer at high temperature would be the fusion of ash into clinker, which would be difficult to remove from the generator. It seems possible that with a properly designed gas producer the temperature could be kept high enough to fuse the ash completely and run it out of the generator in the form of liquid slag, as is done in cupolas and blast furnaces. Experiments along this line were conducted by the Bureau of Mines but had to be discontinued before satisfactory results were obtained. The description of these experiments and the results that were obtained are given in Technical Paper 20.[b]

EXPLOSIONS IN BOILER FURNACES.

As the gases rising from the fuel bed contain 20 to 32 per cent of combustible gases, it is not difficult to understand that under the right conditions an explosive mixture can be formed that might cause an explosion violent enough to injure the fireman. An explosive mixture can be formed in a boiler furnace in either of the two following ways:

(1) With a tight setting and the fire doors completely shut so that no air is entering above the fuel bed, the furnace and the setting are filled with a combustible gas. If then the fire doors are suddenly opened a large volume of air is admitted into the furnace and mixes rapidly with the combustible gas. Under such conditions the

---

[a] Clement, J. K., Adams, L. H., and Haskins, C. N., Essential factors in the formation of producer gas: Bull. 7, Bureau of Mines, 1911, p. 7.

[b] Smith, C. D., The slagging type of gas producer, with a brief report of preliminary tests: Tech. Paper 20, Bureau of Mines, 1912, 12 pp.

combustion of the gases may be so rapid that it assumes the violence of an explosion.

(2) With the fire doors wide open the furnace and the setting fill with air. If then a shovelful of slacky coal is spread over the fuel bed and the fire doors are quickly closed, the large volume of combustible gas rising from the freshly fired coal forms an explosive mixture with the air in the setting. An explosion may follow which is strong enough to blow the fire door open and even lift the hood noticeably from its seat on the setting.

At the experiment station of the Bureau of Mines explosions of the second description were made almost at will. The explosions were made in the experimental furnace having a long combustion chamber which is described in Technical Paper 63.[a] Three simultaneous gas samples were collected during three rapidly successive explosions. The samples were collected at section G (see fig. 3, Tech. Paper 63), about 30 feet from the grate. The time of collecting the samples was about one minute, starting about one-half minute before the first explosion and ending about one-half minute after the third one. The explosions followed each other within about two seconds, and probably were three waves of the same explosion.

Inasmuch as part of the gas sample was collected before and part after the explosions, the analyses in the table below give the composition of a mixture of the gases causing the explosions and the gases resulting from the explosions. Similar explosions were also produced by quickly closing the fire door after raking the fuel bed. The results of the analyses follow:

Composition of furnace gases collected during three successive ***explosions in a*** *furnace having a long combustion chamber.*

[Explosions occurred after spreading a shovelful of slack coal over the grate.]

Sample No.	Proportion in gases of—				
	CO_2.	O_2.	CO.	CH_4.	H_2.
	Per cent.	*Per cent.*	*Per cent.*	*Per cent.*	*Per cent.*
G 3–5	14.3	0.4	4.0	0.2	2.0
16	13.7	.3	5.7	.1	2.6
27	14.1	.4	4.8	.3	2.0

---

[a] Clement, J. K., Frazer, J. C. W., and Augustine, C. E., Factors governing the combustion of coal in boiler furnaces: Tech. Paper 63, Bureau of Mines, 1914, 46 pp.

The explosive limits of H_2, CO, CH_4, and illuminating gas in air as determined by different observers are as follows:

Explosive limits of H_2, CO, CH_4, and illuminating gas in air.

Gas tested.	Lower limit of explosion.	Upper limit of explosion.	Observer.
Hydrogen (H_2)	9.5	64.7	Rosykowski.
Do	9.5	66.3	Bunte and Eitner.
Carbon monoxide (CO)	14.3	74.6	Rosykowski.
Do	17.3	74.8	Bunte and Eitner.
Methane (CH_4)	6.0	12.0	Rosykowski.
Do	6.1	12.8	Bunte and Eitner.
Illuminating gas	7.0	22.6	Rosykowski.
Do	7.9	19.1	Bunte and Eitner.

CONCLUSION.

A summary of the results of the tests described herein and the conclusions drawn therefrom has been given in the first part of this report on pages 8 to 9, and therefore need not be repeated here.

PUBLICATIONS ON FUEL TECHNOLOGY.

A limited supply of the following publications of the Bureau of Mines is temporarily available for free distribution. Requests for all publications can not be granted, and applicants should limit their selection to publications that may be of especial interest to them. Requests for publications should be addressed to the Director, Bureau of Mines, Washington, D. C.

BULLETIN 2. North Dakota lignite as a fuel for power-plant boilers, by D. T. Randall and Henry Kreisinger. 1910. 42 pp., 1 pl., 7 figs.

BULLETIN 4. Features of producer-gas power-plant development in Europe, by R. H. Fernald. 1910. 27 pp., 4 pls., 7 figs.

BULLETIN 5. Washing and coking tests of coal at Denver, Colo., July 1, 1908, to June 30, 1909, by A. W. Belden, G. R. Delamater, J. J. Groves, and K. M. Way. 1910. 62 pp., 1 fig.

BULLETIN 6. Coals available for the manufacture of illuminating gas, by A. H. White and Perry Barker, compiled and revised by H. M. Wilson. 1911. 77 pp., 4 pls., 12 figs.

BULLETIN 14. Briquetting tests of lignite at Pittsburgh, Pa., 1908–9; with a chapter on sulphite-pitch binder, by C. L. Wright. 1911. 64 pp., 11 pls., 4 figs.

BULLETIN 16. The uses of peat for fuel and other purposes, by C. A. Davis. 1911. 214 pp., 1 pl., 1 fig.

BULLETIN 24. Binders for coal briquets, by J. E. Mills. 56 pp., 1 fig. Reprint of United States Geological Survey Bulletin 343.

BULLETIN 27. Tests of coal and briquets as fuel for house-heating boilers, by D. T. Randall. 44 pp., 3 pls., 2 figs. Reprint of United States Geological Survey Bulletin 366.

BULLETIN 28. Experimental work conducted in the chemical laboratory of the United States fuel-testing plant at St. Louis, Mo., January 1, 1905, to July 31, 1906, by N. W. Lord. 51 pp. Reprint of United States Geological Survey Bulletin 323.

BULLETIN 31. Incidental problems in gas-producer tests, by R. H. Fernald, C. D. Smith, J. K. Clement, and H. A. Grine. 29 pp., 8 figs. Reprint of United States Geological Survey Bulletin 393.

BULLETIN 33. Comparative tests of run-of-mine and briquetted coal on the torpedo boat *Biddle*, by W. T. Ray and Henry Kreisinger. 50 pp., 10 figs. Reprint of United States Geological Survey Bulletin 403.

BULLETIN 36. Alaskan coal problems, by W. L. Fisher. 1911. 32 pp., 1 pl.

BULLETIN 39. The smoke problem at boiler plants, a preliminary report, by D. T. Randall. 31 pp. Reprint of United States Geological Survey Bulletin 334, revised by S. B. Flagg.

BULLETIN 40. The smokeless combustion of coal in boiler furnaces, with a chapter on central heating plants, by D. T. Randall and H. W. Weeks. 188 pp., 40 figs. Reprint of United States Geological Survey Bulletin 373, revised by Henry Kreisinger.

BULLETIN 49. City smoke ordinances and smoke abatement, by S. B. Flagg. 1912. 55 pp.

BULLETIN 54. Foundry cupola gases and temperatures, by A. W. Belden. 1913. 29 pp., 3 pls., 16 figs.

BULLETIN 55. The commercial trend of the producer-gas power plant in the United States, by R. H. Fernald. 1913. 93 pp., 1 pl., 4 figs.

BULLETIN 56. First series of coal-dust tests in the experimental mine, by G. S. Rice, L. M. Jones, J. K. Clement, and W. L. Egy. 1913. 115 pp., 12 pls., 28 figs.

BULLETIN 58. Fuel-Briquetting investigations, July, 1904, to July, 1912, by C. L. Wright. 1913. 277 pp., 21 pls., 3 figs.

BULLETIN 76. United States coals available for export trade, by Van. H. Manning. 1914. 15 pp., 1 pl.

BULLETIN 85. Analyses of mine and car samples of coal collected for the fiscal years 1911 to 1913, by A. C. Fieldner, H. I. Smith, A. H. Fay, and Samuel Sanford. 1914. 444 pp., 2 figs.

BULLETIN 89. Economic methods of utilizing Western lignites, by E. J. Babcock. 1915. 73 pp., 5 pls., 5 figs.

BULLETIN 91. Instruments for recording carbon dioxide in flue gases, by J. F. Barkley and S. B. Flagg. 1916. 60 pp., 1 pl., 25 figs.

TECHNICAL PAPER 2. The escape of gas from coal, by H. C. Porter and F. K. Ovitz. 1911. 14 pp., 1 fig.

TECHNICAL PAPER 5. The constituents of coal soluble in phenol, by J. C. W. Frazer and E. J. Hoffman. 1912. 20 pp., 1 pl.

TECHNICAL PAPER 8. Methods of analyzing coal and coke, by F. M. Stanton and A. C. Fieldner. 1913. 42 pp., 12 figs.

TECHNICAL PAPER 9. The status of the gas producer and of the internal-combustion engine in the utilization of fuels, by R. H. Fernald. 1912. 42 pp., 6 figs.

TECHNICAL PAPER 10. Liquefied products of natural gas; their properties and uses, by I. C. Allen and G. A. Burrell. 1912. 23 pp.

TECHNICAL PAPER 16. Deterioration and spontaneous combustion of coal in storage, a preliminary report, by H. C. Porter and F. K. Ovitz. 1912. 14 pp.

TECHNICAL PAPER 34. Experiments with furnaces for a hand-fired return tubular boiler, by S. B. Flagg, G. C. Cook, and F. E. Woodman. 1914. 32 pp. 1 pl., 4 figs.

TECHNICAL PAPER 35. Weathering of the Pittsburgh coal bed at the experimental mine near Bruceton, Pa., by H. C. Porter and A. C. Fieldner. 1914. 35 pp., 14 figs.

TECHNICAL PAPER 37. Heavy oil as fuel for internal combustion engines, by I. C. Allen. 1913. 36 pp.

TECHNICAL PAPER 38. Wastes in the production and utilization of natural gas, and methods for their prevention, by Ralph Arnold and F. G. Clapp. 1913. 29 pp.

TECHNICAL PAPER 45. Waste of oil and gas in the Mid-Continent fields, by R. S. Blatchley. 1914. 54 pp. 2 pls., 15 figs.

TECHNICAL PAPER 49. The flash point of oils, methods and apparatus for its determination, by I. C. Allen and A. S. Crossfield. 1913. 31 pp., 2 figs.

TECHNICAL PAPER 50. Metallurgical coke, by A. W. Belden. 1913. 48 pp., 1 pl., 23 figs.

TECHNICAL PAPER 55. The production and use of brown coal in the vicinity of Cologne, Germany, by C. A. Davis. 1913. 15 pp.

TECHNICAL PAPER 57. A preliminary report on the utilization of petroleum and natural gas in Wyoming, by W. R. Calvert, with a discussion of the suitability of natural gas for making gasoline, by G. A. Burrell. 1913. 23 pp.

TECHNICAL PAPER 63. Factors governing the combustion of coal in boiler furnaces; a preliminary report, by J. K. Clement, J. C. W. Frazer, and C. E. Augustine. 1914. 46 pp., 26 figs.

TECHNICAL PAPER 64. The determination of nitrogen in coal, a comparison of various modifications of the Kjeldahl method with the Dumas method, by A. C. Fieldner and C. A. Taylor. 1915. 25 pp., 5 figs.

TECHNICAL PAPER 65. A study of the oxidation of coal, by H. C. Porter. 1914. 30 pp., 12 figs.

TECHNICAL PAPER 74. Physical and chemical properties of the petroleums of California, by I. C. Allen, W. A. Jacobs, A. S. Crossfield, and R. R. Mathews. 1914. 38 pp., 1 fig.

TECHNICAL PAPER 76. Notes on the sampling and analysis of coal, by A. C. Fieldner. 1914. 59 pp., 6 figs.

TECHNICAL PAPER 93. Graphic studies of ultimate analyses of coals, by O. C. Ralston, with a preface by H. C. Porter. 1915. 41 pp., 3 pls., 6 figs.

TECHNICAL PAPER 97. Saving fuel in heating a house, by L. P. Breckenridge and S. B. Flagg. 1915. 35 pp., 3 figs.

TECHNICAL PAPER 104. Analysis of natural gas and illuminating gas by fractional distillation at low temperatures and pressures, by G. A. Burrell, F. M. Seibert, and I. W. Robertson. 1915. 41 pp., 7 figs.

TECHNICAL PAPER 112. The explosibility of acetylene, by G. A. Burrell and G. G. Oberfell. 1915. 15 pp.

TECHNICAL PAPER 113. Some properties of the water in coal, by H. C. Porter and O. C. Ralston. 1916. 30 pp., 3 figs.

TECHNICAL PAPER 123. Notes on the use of low-grade fuel in Europe, by R. H. Fernald. 1915. 37 pp.

PUBLICATIONS THAT MAY BE OBTAINED ONLY THROUGH THE SUPERINTENDENT OF DOCUMENTS.

The editions for free distribution of the following Bureau of Mines publications are exhausted, but copies may be obtained by purchase from the Superintendent of Documents, Government Printing Office, Washington, D. C., or can be consulted at public libraries. Prepayment of the price is required and should be made in cash (exact amount) or by postal or express money order payable to the Superintendent of Documents.

The Superintendent of Documents is an official of the Government Printing Office, and is not connected with the Bureau of Mines.

BULLETIN 1. The volatile matter of coal, by H. C. Porter and F. K. Ovitz. 1910. 56 pp., 1 pl., 9 figs. 10 cents.

BULLETIN 3. The coke industry of the United States as related to the foundry, by Richard Moldenke. 1910. 32 pp. 5 cents.

BULLETIN 7. Essential factors in the formation of producer gas, by J. K. Clement, L. H. Adams, and C. N. Haskins. 1911. 58 pp., 1 pl., 16 figs. 10 cents.

BULLETIN 9. Recent development of the producer-gas power plant in the United States, by R. H. Fernald. 1910. 82 pp., 2 pls., 15 cents. Reprint of United States Geological Survey Bulletin 416.

BULLETIN 11. The purchase of coal by the Government under specifications, with analyses of coal delivered for the fiscal year 1908–9, by G. S. Pope. 80 pp., 10 cents. Reprint of United States Geological Survey Bulletin 428.

BULLETIN 12. Apparatus and methods for the sampling and analysis of furnace gases, by J. C. W. Fraser and E. J. Hoffman. 1911. 22 pp., 6 figs. 5 cents.

BULLETIN 13. Résumé of producer-gas investigations, October 1, 1904, to June 30, 1910, by R H. Fernald and C. D. Smith. 1911. 393 pp., 12 pls., 250 figs. 65 cents.

BULLETIN 18. The transmission of heat into steam boilers, by Henry Kreisinger and W. T. Ray. 1912. 180 pp., 78 figs. 20 cents.

BULLETIN 22. Analyses of coals in the United States, with descriptions of mine and field samples collected between July 1, 1904, and June 30, 1910, by N. W. Lord, with chapters by J. A. Holmes, F. M. Stanton, A. C. Fieldner, and Samuel Sanford. 1912. Part I, Analyses, pp. 1–321; Part II, Descriptions of samples, pp. 321–1129. 85 cents.

BULLETIN 23. Steaming tests of coals and related investigations, September 1, 1904, to December 31, 1908, by L. P. Brekenridge, Henry Kreisinger, and W. T. Ray. 1912. 380 pp., 2 pls., 94 figs. 50 cents.

BULLETIN 29. The effect of oxygen in coal, by David White. 80 pp., 3 pls. 20 cents. Reprint of United States Geological Survey Bulletin 382.

BULLETIN 30. Briquetting tests at the United States fuel-testing plant, Norfolk, Va., 1907–8, by C. L. Wright. 1911. 41 pp., 9 pls., 15 cents. Reprint of United States Geological Survey Bulletin 385.

BULLETIN 32. Commercial deductions from comparisons of gasoline and alcohol tests on internal-combustion engines, by R. M. Strong. 38 pp. 5 cents. Reprint of United States Geological Survey Bulletin 392.

Original from PRINCETON UNIVERSITY

BULLETIN 34. Tests of run-of-mine and briquetted coal in a locomotive boiler, by W. T. Ray and Henry Kreisinger. 33 pp., 9 figs. Reprint of United States Geological Survey Bulletin 412.

BULLETIN 35. The utilization of fuel in locomotive practice, by W. F. M. Goss. 29 pp., 8 figs. Reprint of United States Geological Survey Bulletin 402.

BULLETIN 41. Government coal purchases under specifications, with analyses for the fiscal year 1909–10, by G. S. Pope, with a chapter on the fuel-inspection laboratory of the Bureau of Mines, by J. D. Davis. 1912. 97 pp., 3 pls., 9 figs. 15 cents.

BULLETIN 43. Comparative fuel values of gasoline and denatured alcohol in internal-combustion engines, by R. M. Strong and Lauson Stone. 1912. 243 pp., 3 pls., 32 figs. 20 cents.

BULLETIN 63. Sampling coal deliveries and types of Government specifications for the purchase of coal, by G. S. Pope. 1913. 68 pp., 4 pls., 3 figs. 10 cents.

BULLETIN 97. Sampling and analysis of flue gases, by Henry Kreisinger and F. K. Ovitz. 1915. 68 pp., 1 pl., 37 figs. 15 cents.

TECHNICAL PAPER 1. The sampling of coal in the mine, by J. A. Holmes. 1911. 18 pp., 1 fig. 5 cents.

TECHNICAL PAPER 3. Specifications for the purchase of fuel oil for the Government, with directions for sampling oil and natural gas, by I. C. Allen. 1911. 13 pp. 5 cents.

TECHNICAL PAPER 25. Methods for the determination of water in petroleum and its products, by I. C. Allen and W. A. Jacobs. 1912. 13 pp., 2 figs. 5 cents.

TECHNICAL PAPER 26. Methods for the determination of the sulphur content of fuels, especially petroleum products, by I. C. Allen and I. W. Robertson. 1912. 13 pp., 1 fig. 5 cents.

TECHNICAL PAPER 109. Composition of the natural gas used in 25 cities, with a discussion of the properties of natural gas, by G. A. Burrell and G. G. Oberfell. 1915. 22 pp. 5 cents.

TECHNICAL PAPER 114. Heat transmission through boiler tubes, by Henry Kreisinger and J. F. Barkley. 1915. 36 pp., 23 figs. 10 cents.

TECHNICAL PAPER 115. Inflammability of mixtures of gasoline vapor and air, by G. A. Burrell and H. T. Boyd. 1915. 18 pp., 2 figs. 5 cents.

INDEX.

A.

Page.

- **Adams, L. H.,** on reduction of carbon dioxide in fuel bed______ 46
- **Air,** admission of, to fuel bed_____ 52–55
    - factors governing____ 12
    - figure showing_______ 45
  - in ash pit, pressure of________ 27–37
  - leakage of__________________ 53, 54
  - rate of feeding, effect of______ 51
    - figure showing________ 52, 53
    - on rate of oxidation___ 46
  - weight of, needed for combustion, factors affecting________ 58
- **Air supply** for boiler furnace____ 8, 9, 11
  - effect of, on distillation of volatile matter____________ 48
    - on gases in fuel bed______ 45
  - excess, objections to__________ 53, 54
  - measurement of______________ 18
  - over fuel bed, need of_________ 9
  - relation of, to pressure in ash pit __________________ 55, 56
    - figure showing_______ 56
    - to weight of fuel burned__ 8, 9
  - weight of __________________ 27–37
- **Alaska coal.** *See* Bering River coal.
- **Anthracite,** analysis of____________ 17
  - combustion of, pressure drop through fuel bed during_ 57
    - figure showing_______ 56
    - gases from_______________ 38
      - composition of, figures showing___________ 41, 42
  - results of tests with__________ 31–34
- **Ash** in coal, distribution of________ 45
    - fusion temperature of_____ 61
  - in coke, distribution of________ 45
  - in fuel bed, effect of, on air supply _________________ 56
    - fusion of__________________ 60, 61
  - fusibility of, factors in________ 9
- **Ash pit,** pressure of air in_________ 27–37
    - relation of, to air supply__ 55, 56
      - figure showing_______ 56

B.

- **Barker, Perry,** analyses of furnace gases by______________ 62
- **Bering River coal,** after heating, view of _______________ 58

Page.

- **Boiler furnace,** air supply in______ 11
  - explosions in, causes of_______ 65, 66
    - gases produced during____ 66
  - operation of, results of________ 9
- **Bituminous coal,** combustion of, gases from____________ 38
  - composition of gases from, figures showing___________ 39–40
  - results of tests with__________ 27–31
  - *See also* Pittsburgh coal.
- **Bureau of Mines,** investigation of___ 7, 8

C.

- **Carbon dioxide** as product of combustion________________ 10
  - in furnace gases, determination of____________________ 24, 62
    - distribution of___________ 45
    - proportion of__ 27–38, 62, 63, 64
      - figures showing______ 39–44
    - reduction of, figure showing ___________________ 47
      - rate of_______________ 46
- **Carbon monoxide,** as product of combustion _______________ 10
  - explosive limits of____________ 67
  - in fuel bed, formation of, factors affecting, figure showing_ 47
  - in furnace gases, determination of____________________ 24, 62
    - proportion of ___ 27–37, 62, 63, 64
  - *See also* Combustible.
- **Chain grate,** feeding of coal and air to_________________ 14
- **Clement, J. K.,** on reduction of carbon dioxide in fuel bed__ 46
- **Clinker** in fuel bed, effect of, on air supply _________________ 56
    - formation of__________ 9, 60, 61
      - figure showing zone of_ 61
  - objections to_________________ 54
- **Coal,** combustible ingredients of____ 10
  - combustion of, in furnace____ 10
    - products of _____________ 10
  - nature of, effect of, on pressure in ash pit_____________ 57
  - rate of burning, factors affecting ___________________ 12
  - *See also* Anthracite coal; Bituminous coal; Pittsburgh coal; Combustion.

Page.

- Coke, analysis of ... 17
  - combustion of, reduction in, figure showing ... 47
  - effect of, on pressure in ash pit ... 57
    - figure showing ... 56
  - gases from, combustion of ... 38
    - composition of, figures showing ... 43, 44
  - results of tests with ... 34–37
- Combustible, burned in tests, relation of, to air supply ... 27–37
  - definition of ... 25
  - gaseous, in fuel bed, composition of ... 38
    - determination of ... 62
    - distribution of ... 45
    - proportion of ... 27–38, 50, 64
      - factors affecting ... 38
      - figures showing ... 39–44
      - weight of, relation of, weight of air to ... 58
    - *See also* Carbon monoxide; Hydrocarbons, unsaturated; Hydrogen; Methane.
- Combustion in fuel bed, complete, factors governing ... 51, 52
  - effect of air supply on ... 51
    - figure showing ... 52, 53
  - factor governing ... 45
  - processes of ... 45, 46
- Combustion of coal, definition of ... 10
  - rapid, factors governing ... 12
  - rate of, variations in ... 8
- Combustion space, gases in, burning of ... 10
  - composition of, figure showing ... 11
    - variations in ... 10, 11

D.

- Distillation in fuel bed, rate of, factors governing ... 48
  - zone of ... 48
- Durley, R. J., cited ... 18

E.

- Explosions in furnaces, causes of ... 65, 66
  - gases produced during ... 66

F.

- Feild, A. L., on fusion temperature of coal ash ... 61
- Fieldner, A. C., on fusion temperature of coal ash ... 61
- Frazer, J. C. W., analysis of samples by ... 63
- Fuel bed, combustion of coal in, gases from ... 10
  - processes of ... 45, 46
  - function of ... 8

Page.

- Fuel bed, gases in, composition of ... 9–11
    - figures showing ... 11, 39–44
  - distribution of ... 38–45
  - holes in, results of ... 38, 53, 54
  - of experimental furnace, temperatures in ... 27–37
  - pressure drop through, factors governing ... 56–60
    - figure showing ... 56
  - rate of combustion in ... 50
  - rate of distillation in ... 48
  - rate of reduction in, factors governing ... 46
  - reactions in, factors governing ... 14, 15
  - temperature in ... 9
  - thick, objections to ... 9, 54, 55
  - thickness of ... 8, 50
    - determination of ... 18
    - during tests ... 27–37
    - effect of, on pressure drop ... 59
    - relation of composition of gases to, figures showing ... 39–44
  - what constitutes ... 9
  - zones in. *See* Distillation zone; Oxidizing zone; Reducing zone.
- Fuel for tests, analyses of ... 17
  - method of weighing ... 18
  - weight of ... 27–37
    - relation of, to weight of air supply ... 27–37
    - *See also* Anthracite; Coke; Pittsburg coal.
- Furnace walls, leakage of air through ... 54
- Furnaces, commercial, types of ... 13, 14
  - design of, factors in ... 12
  - experimental, description of ... 15–17
    - figure showing ... 16
    - fuels used in ... 8, 15
    - tests in, duration of ... 17, 27–37
      - method of conducting ... 17, 18
      - results of ... 25–37
    - thickness of fuel bed in ... 15
    - view of ... 16
  - leakage in settings of ... 54
  - *See also* Boiler furnaces; Hand-fired furnace.

G.

- Gas container, construction of ... 23
  - figure showing ... 24
  - purpose of ... 23
- Gas producers, operation of, difficulties in ... 65
    - factors affecting ... 65
- Gas samplers, construction of ... 21
    - figure showing ... 22
  - distribution of, in furnace ... 21
- Gases from combustion of coal ... 10
  - in fuel bed, composition of ... 8, 27–37
    - points of sampling ... 27–37

Page.

- Gases in furnace, analysis of ---- 23, 24
  - composition of, figure showing ---- 11
  - sampling of ---- 19
    - apparatus for ---- 19
      - figure showing ---- 20
  - *See also* Carbon dioxide; Carbon monoxide; Hydrogen; Illuminating gas; Methane; Oxygen.
- Gregg, E. T., acknowledgment to ---- 8

H.

- Hall, A. E., on fusion temperature of coal ash ---- 61
- Hand-fired furnace, feeding of ---- 13, 14
  - figure showing ---- 13
  - for tests, advantages of ---- 16, 17
  - objections to ---- 14
  - *See also* Furnace, experimental.
- Haskins, C. N., on reduction of carbon dioxide in fuel bed ---- 46
- Heine boiler, tests with, gases from ---- 61, 62
- Holes in fuel bed, leakage of air through ---- 53
  - effect of ---- 54–55
- Hydrocarbons, unsaturated, in furnace gases, determination of ---- 24, 62
  - proportion of ---- 27–37, 64
  - *See also* Combustible, gaseous.
- Hydrogen as product of combustion ---- 10
  - explosive limits of ---- 67
  - in furnace gases, determination of ---- 24, 62
    - proportion of ---- 27–37, 50, 62, 63, 64
  - *See also* Combustible.

I.

- Illuminating gas, explosive limits of ---- 67

J.

- Jones underfeed stoker, fuel bed of, gases from analysis of ---- 64
  - collection of ---- 63
  - figure showing ---- 64

M.

- Methane as product of combustion ---- 10
  - explosive limits of ---- 67
  - in furnace gases, determination of ---- 24, 62
    - proportion of ---- 27–37, 50, 62–64
  - *See also* Combustible.
- Murphy stoker, feeding of coal and air to ---- 14
  - fuel bed of, composition of gases from ---- 62, 63

N.

Page.

- Nitrogen in furnace gases, proportion of ---- 27–37, 64

O.

- Oxidation in fuel bed, rate of, factors governing ---- 46
- Oxidizing zone in fuel bed ---- 46
- Oxygen in fuel bed, distribution of ---- 45
  - proportion of, figures showing ---- 39–44
  - in furnace gases, determination of ---- 24, 62
    - proportion of ---- 27–38, 62–64

P.

- Pittsburgh coal, after heating, view of ---- 58
  - analysis of ---- 17
  - composition of gases from, figures showing ---- 39, 40
  - effect of, on pressure in ash pit ---- 57
    - figure showing ---- 56
  - gases from combustion of ---- 38
  - results of tests with ---- 27–31
  - *See also* Bituminous coal.
- Pressure drop, apparent and true, relation between, figure showing ---- 60
  - factors governing ---- 56–60
  - true, determination of ---- 59

R.

- Reducing zone, definition of ---- 46, 61
- Roney stoker, feeding of coal and air to ---- 14

S.

- Side-feed furnace, feeding of coal and air to ---- 14
  - figure showing ---- 13
- Smith, A. L., acknowledgment to ---- 8
- Smoke, formation of, cause of ---- 49
  - proportion of tar in ---- 49
- Soot in furnace gases, collection of ---- 21
  - determination of ---- 20, 21, 25
  - difficulty of burning ---- 49
  - proportion of ---- 49–50
  - weight of ---- 27–37
    - relation of, to weight of combustible ---- 49
- Stokers, mechanical. *See* Jones underfeed, Murphy stoker, Roney stoker.

T.

- Tar, collection of, in furnace ---- 20
  - combustion of, difficulties in ---- 49
  - in furnace gases, determination of ---- 25
    - proportion of ---- 49, 50
    - weight of ---- 27–37
      - relation of, to weight of combustible ---- 49

Page.

Temperatures in fuel bed 27–38
  effect of, on rate of distillation 48
    on rate of reduction 46, 48
    on reduction of carbon dioxide, figure showing 47
  measurement of 18, 19, 49
  variations in 38, 51
    figures showing 39–44

U.

Underfeed stoker, feeding of coal and air to 14

Page.

Underfeed stoker, figure showing 13
  See also Jones underfeed stoker.

V.

Volatile matter in fuel bed, distillation of, factors governing 48

W.

Water vapor as product of combustion 10